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New technologies to accelerate additive manufacturing processes on an industrial scale"

MEMÒRIA

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Abstract

This research project is a study of the additive manufacturing technology, from a point of view of the current challenges that this technology faces in their process.

The main intention of this project is to study and discuss AM technology in today's world, making also a forecast of the development of this technology.

In a primary phase, will be presented a state of the art of 3D printing and how it stands nowadays, after that, are presented some materials and processes, comparing the materials depending the strength and weaknesses.

Then, a discussion of 3D printing's importance in the overall industry will take place, as well as an analysis of AM process of polymers and metals. It will be discussed the current path of AM development in Aeronautical, Automobile and Medical sector.

Finally, we analyse some economic issues regarding 3D printing and the changes it can induce on the overall supply chain. We also concluded two interviews, the first in a technology foundation in Catalunya-Spain, and the other in a medtech company.

Keywords: Additive Manufacturing, polymer and metal printing, additive processes, challenges and applications.

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1. Introduction

This research project was developed in the course research assignment for exchange students, under the ERASMUS + Programme, with the cooperation of the UPC - Polytechnic University of Catalunya.

This document had the support of the Department of Strength of Materials and Structural Engineering from UPC, and was developed during the academic year of 2018/2019, during the first semester.

1.1. Project framework and motivation

In recent years, companies have been subjected to the reduction of costs and delivery times, while at the same time need to increase the quality and performance of new products launched in the market.

Nowadays, additive manufacturing (AM) is causing changes in the entire value creation models, strategies, systems and processes.

This recent technology is proving, day after day, that it has the potential to revolutionize the global parts manufactured and logistics landscape, also bringing changes in the internal and external environment of a company, for example on time to market strategies, product variety and customer satisfaction.

This project intends to study AM's current situation in the industry as well as making a forecast to what it can represent in a near future.

1.2. Objectives

This project has the following objectives:

- Study and discussion of AM technology in today's world.
- AM Process analyses of polymers and metals.
- Discussion of solutions for the main challenges of AM.
- Forecast of AM development in industry.

1.3. Methodology

The approach used to build this project was based on papers and articles published by recognized institutions. Also, participating and gathering information from fairs and conferences around the subject AM technology and by visiting companies.

During the search for information, some recent document and reports were blocked to the free viewer, that's why this project have some information, like studies and statistics, with two years old.

1.4. Project Structure

In a first phase, will be presented a state of the art of 3D printing and how it stands nowadays, after that, are presented some materials and processes, comparing them, in terms of strength and weaknesses.

Then, an AM introduction will be made as well as an analysis of AM process of polymers and metals. Then, will be discussed the current path of AM development in Aeronautical, Automobile and Medical sector.

The second part cover the main challenges of today's AM in several industries with the follow up of evidencing 3D printing's roll on the overall market.

In the final part, 3D printing's impact on the overall industry will be reported.

2. State of art

This chapter contains the principles of the latest development concerning AM technologies.

2.1. History of additive manufacturing

Additive manufacturing is generally considered a new or emerging technology of the 21st century. Although the first AM techniques became accessible at the end of the 1980s with the name “Rapid Prototyping” [1], its history dates to since 1960s, when Professor Herbert Voelcker wondered about the possibilities of doing "something interesting" by using automatic machine tools, controlled by a computer [2].

During the 1970s, Voelcker has developed basic mathematical tools to describe dimensional aspects, resulting in the first mathematical and algorithmic theories for modelling of solids. In 1987 Carl Deckard, a researcher at the University of Texas, has come up with a revolutionary idea, pioneering the manufacture based on layers, printing three-dimensional models using laser light to fuse powder in solid prototypes [3]. Deckard called this sintering technique (SLS, Selective Laser Sintering), with extremely promising results. The investigations by Voelcker and Deckard gave a boost to this new industry, there are, however, other references from pioneers in the field of AM.

However, industry recognizes Charles Hull as the “father” of AM. Charles Hull was the co-founder of the American company *3D Systems* and patented in 1987 the first additive process: Stereolithography (SLA). *SLA* is a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer, using a laser [3].

This machine operates through the principle of stereolithography and, for the first time, enabled users to create a physical object from digital data [4].

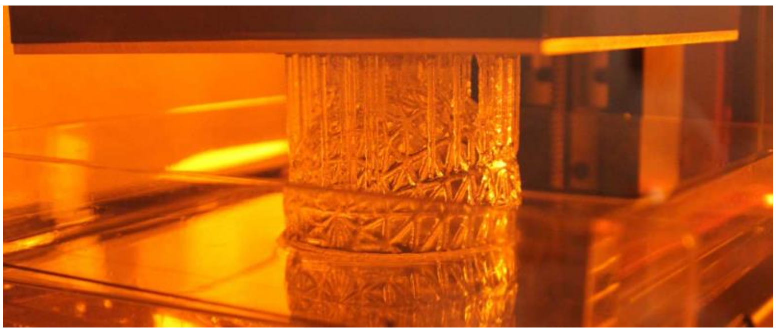

Figure 1 - Production of a piece with Stereolithography (SLA) [4].

In 1988, Carl Deckard patents a selective laser sintering (SLS) technology, and one year after Scoot Crump patent a fused deposition modelling (FDM), making the third main 3D printing technologies [3].

In the years ahead, many additive manufacturing systems appear. In 1992, *DTM* produced the world's first selective laser sintering (SLS) machine, that shoots a laser at a powder instead of a liquid [1].

In 1994 other technologies and systems appear, such as [2]:

- ModelMaker, of the American company Sanders Prototype, using jet system ink-jet wax;
- Solid Center, of the Japanese company Kira Corp., using a laser system and an XY plotter to produce moulds and prototypes by lamination of paper;
- Stereolithography system from Fockele & Schwarze (Germany);
- EOSINT system of the German company EOS, based on sintering;
- Stereolithography system of the Japanese company Ushio.

The birth of medical 3D bioprinting, with the first organ successfully transplanted to a patient, occurred in 1999.

In the middle of 2000, Adrian Bowler founds the *RepRap* open source project, with the goal to build a 3D printer that could print its own components, approximately 57% of its mechanical components. The project *RepRap* (Replicating Rapid Prototyper) has the objective to produce a free software and with open access to the code of the 3D printer. In scope of this programme, the printer *Darwin* born in 2004 [2].

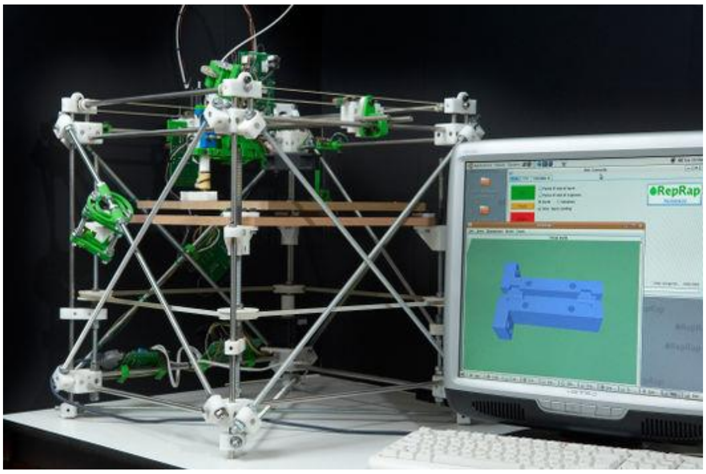

Figure 2 - First 3DP machine RepRap – Darwin [5].

In 2005 a company called *ZCorp* launches the "Spectrum Z510" the first high definition colour 3D printer [3].

The printing of the first prosthetic limb, gave an important up rise to the 3DP medical sector, that event happen in 2008. And, in the same year, in the Netherlands, a on-demand 3D printing service was created, making 3DP widely accessible [6].

Another important event that was decisively to foresee de 3D potential happen when the first car and aircraft was printed, in 2011. In the picture below, we see the first aircraft printed, with a weight of 21 kilograms, and less than 4 meters of length [7], developed by the aircraft manufacturer Airbus.

Figure 3 - World first aircraft printed, named “Thor” by Airbus [7].

Over the past years, AM is experiencing a rapid development, acquiring interest in many areas, such as: aerospace, automotive, biomedical, energy, and others. The consequence of this development was the high price drop of this machines, and a better way to find any kind of model in the market, which is very attractive both to industry as to the public as final consumer [2].

According to *Ernest & Young* ®, a multinational services company, in 2016 they performed a study of the 3DP presence in the industry world, after collecting data from 900 different-sized companies worldwide, and from different sectors.

This survey show that 3D printing has mushroomed between (2011 to 2016), and, in 2016 approximately 24% of the companies surveyed, already have experience with 3DP. This survey also shows that one in three companies with 3DP experience are already applying the technology for direct manufacturing, and, as shown in the following picture, the plastics is the most relevant, but is closely followed by four other important sectors [8].

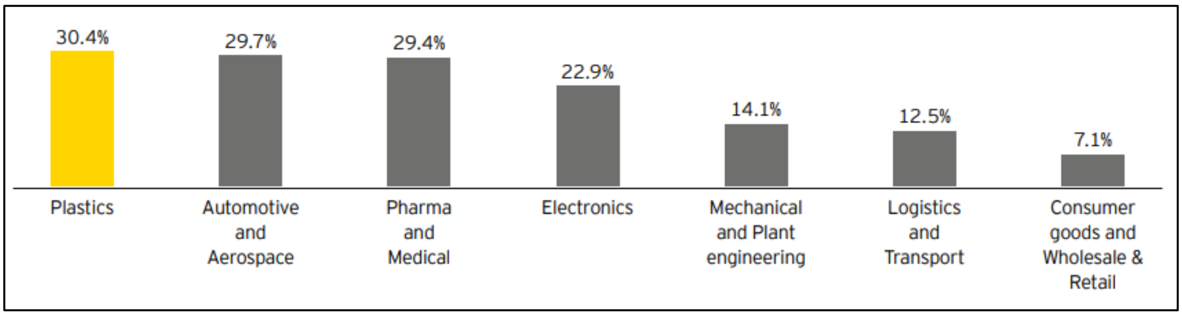

Figure 4 - Percentage of direct manufacturing made by industries that already experience 3DP [8].

The same survey makes some forecasts too, one is that China and South Korea will have a big development and investment to maintain the position as the global producer of goods, with the expectation to use additive manufacturing to produce end products, in more than half of their companies [8].

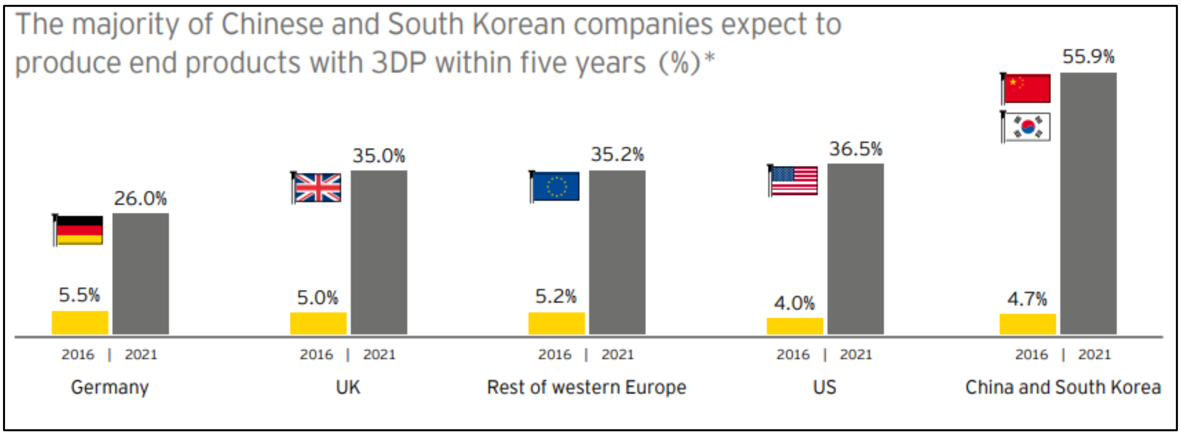

*Figure 5 - Forecast of 3DP to produce end products (*N=900 companies)*

A recent Wohler's' report forecasts shows that AM industry will grow from $6.1 billion in 2016 to $21 billion by the year 2020. The biomedical market represents 11% of the total AM market share today and is going to be one of the drivers for AM evolution and growth [9].

2.2. Introduction to AM

The term Additive Manufacturing is the most technically designation, but it is known also by the name of 3D printing. AM covers a diverse range of processes and technologies, with the ability to build physical objects directly from 3D Computer Aided Design (CAD) data. AM adds liquid, sheet, wire or other powdered materials to form component parts or products. [10].

This manufacturing methodology differs from subtractive production methods or mould injection, traditionally employed. These usually starts the activity with a block, or a certain amount of material, which are being adapted by means of various techniques, such as cutting, drilling and grinding, until the desired format is achieved. This kind of process produces a large volume of waste, translating in negative aspects at all levels: efficiency, economy and sustainability [10].

Additive Manufacturing on the other hand can execute exactly the form/shape determined by the digital model, tending to use only the material strictly necessary (there may be waste but with low rates). This process also has advantages in the customization of the object, being able to execute in a single session the desired object, thus consolidating several steps in a single process [11].

The main difference between AM and other processes is that AM builds products layer-by layer, additively, rather than by subtracting material from a larger piece of material like cutting out a landing gear from a block of steel, that is, “subtractive” manufacturing [12].

For example, if it is desired to produce a hollow sphere, with additive method it can be done in a single process, while with subtractive process it will have to be created, for example, two hemispheres to which the interior will be removed, and which will then have to be melted together. AM do not, therefore, imply the production of several parts and consequent doesn’t need for assembly (which also has positive effects in terms of planning and control) [10].

One advantage of 3D printing is the reduction of the lead time of a product, that is, the total time that elapses from the entrance of the material to its exit from the inventory. Since technology is geared to local production, with consideration of its particularities and needs, it may also cause changes or even a paradigm shift in relation to the logistics and mode of operation of traditional supply chains.

AM has been evolving over the past 30 years and 36% of companies are already applying or intend to apply AM (2016), in which, the aerospace, defence and automotive are the most mature sectors where AM is leveraging business [8].

Awareness of AM technology is reaching the market by the endless winnings that brings, across the value chain of a company, for example [13]:

- **Quality and speed**: The printer’s speed is increasing each day, and quality assurance tools integrated into the printers makes possible a better validation and inspection;
- **Material availability**: Yet a challenge but each day becomes clear the path of a big number of materials, where companies could choose;
- **Workforce knowledge**: The young community of designers, engineers and

enthusiasts are reaching the market with the knowledge and the tools to make I flourish even more;

- **Executive Interest:** The factors presented before are making the executives more open when evaluating AM, the way this technology could change their business, and how to integrate it in the conventional manufacturing process of the company. The discussion is now about implementing AM in design and production, and not only in the prototyping step;
- **Product development:** In the way that allow the decrease of time-to-market products, and shortens the phase of development, which means smaller design cycles;
- **Manufacturing:** Reduced process time via improved tools and reduced waste;
- **Engineering and maintenance:** More flexible maintenance processes and reduced maintenance costs;
- **Logistics and warehousing:** Reduced inventory which decreases logistics costs;
- **Aftermarket:** Increased flexibility in delivery of spare parts and reduced costs of spare parts production.

3. Materials and requirements

Choosing the right material to print a certain object is no easy task and it has been becoming even harder as the 3D printing market is constantly seeing the new appearance of radically new materials. We are going to focus on the most used type of materials those being polymers and metals.

To choose the material, normally these are graded along 3 categories: mechanical performance, visual quality, and process.

3.1. Polymers

The wide range of polymers used in the 3D printing process encompasses thermosets, elastomers, hydrogels, thermoplastics, functional polymers, polymer blends, biological systems and composites. Their properties enhance their use on the process in what concerns design, processing parameters as well as increasing production speed along with improved accuracy, functionality, surface finish, mechanical properties, stability and porosity.

Their use is exploited in many industries going from lightweight engineering, architecture, food processing, optics, energy technology, dentistry, drug delivery and personalized medicine. Unlike other materials like metals and ceramics, polymers are essential on the advances that have been made in the emerging AM of advanced multifunctional and multi-material systems such as biological systems and synthetic systems[14].

On the appendixes we can find a table that summarizes some of the processes that use polymers.

3.1.1. Properties

In order to access the properties of the polymers to be used in 3D printing, a spider web graph can be used with the focus on key properties the polymer at hand must have to better fulfil his job.

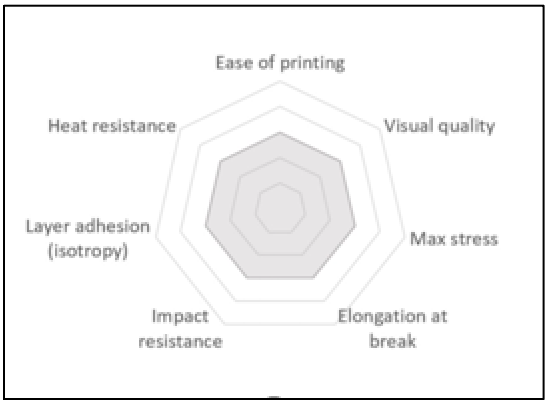

Figure 6 - Spider web graph with some of the properties to be compared [15].

- ✓ Ease of printing – The easiness to print a material, it evaluates bed adhesion, max printing speed, frequency of failed prints, flow accuracy, ease to feed into the printer, etc;
- ✓ Heat resistance – Max temperature the final object can sustain before softening and posteriorly deforming;
- ✓ Layer adhesion (isotropy) – This property is linked to the isotropy of the final gathered object. The uniformity in all directions of properties of the final piece is better if the layer adhesion is as well;
- ✓ Impact resistance – Energy needed to bring an object to rupture with a sudden impact;
- ✓ Elongation at break – Length to which the object has been extended to before breaking;
- ✓ Max stress – Maximum stress supported by the object before breaking when being submitted to a traction test;
- ✓ Visual quality – How good the piece's surface looks when finished printing[15].

3.1.2. Advantages and disadvantages

In what concerns polymers, the most used ones, meaning that they gather the most appealing properties for objects to hold when being on their work position, are:

- PLA (Polylatic acid)

PLA provides a good visual quality after printing, is very rigid and relatively strong, however is very brittle. Furthermore, it is the easiest polymer to print with.

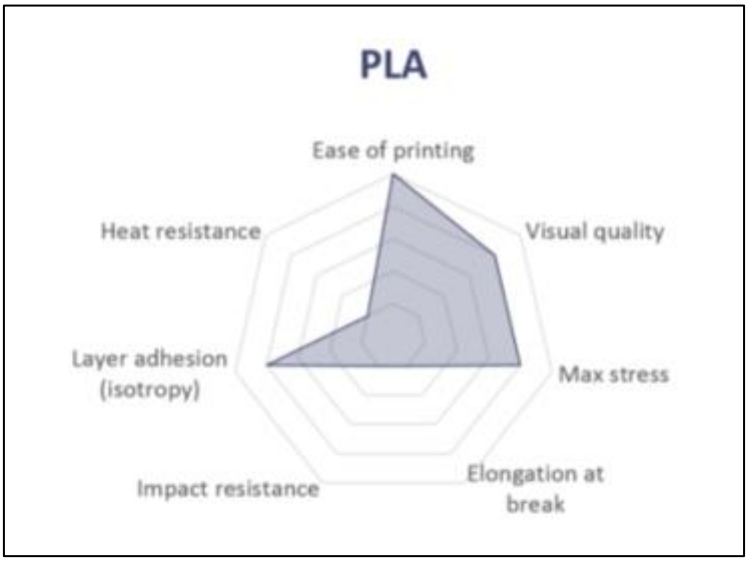

Figure 7 - PLA Spider web chart[15].

Table 1 - PLA pros and cons[15].

Advantages	Disadvantages
Biosourced, Biodegradable	Can't be glued easily
Odorless	Low humidity resistance
Can be post-processed with sanding paper and painted with acrylics	
Good UV resistance	

- ABS (Acrylonitrile butadiene styrene)

This polymer is normally picked over PLA when it is required for the piece to have higher toughness and temperature resistance.

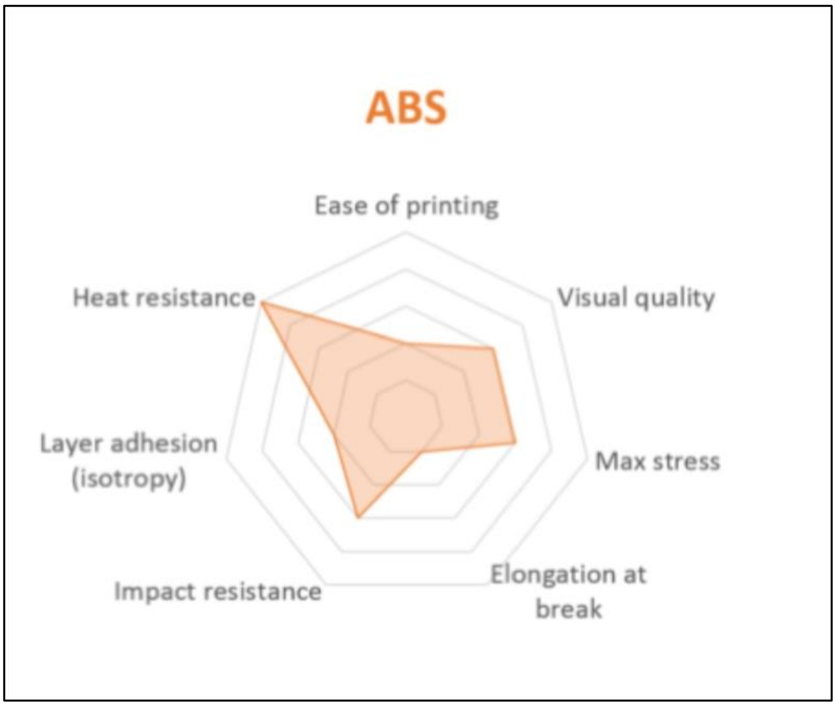

Figure 8 - ABS spider web chart[15].

Table 2 - ABS pros and cons[15].

Advantages	Disadvantages
Can be post-processed with acetone vapors for a glossy finish	Odor when printing
Can be post-processed with sandind paper and painted with acrylics	Potentially high fume emissions
Acetone can also be used as strong glue	UV sensitive
Good abrasion resistance	

- PET (Polyethylene terephthalate)

Because it is hydrolysed, it needs caution when used on 3D printing, it has to be well dried before being used. Some AM suppliers have developed PETG (Polyethylene terephthalate glycol-modified) which is more tough and heat resistant than PLA and easier to print than ABS.

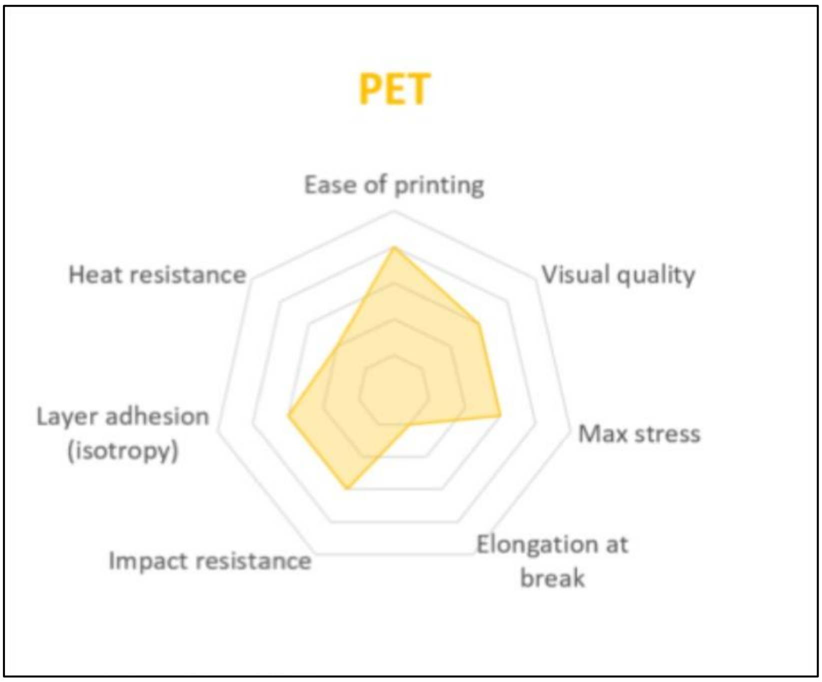

Figure 9 - PET spider pie chart[15].

Table 3 - PET pros and cons[15].

Advantages	Disadvantages
High humidity resistance	Heavier than PLA and ABS
High chemical resistance	
Recyclable	
Good abrasion resistance	
Can be post-processed with sanding paper and painted with acrylics	

- Nylon

Nylon is a polymer with great mechanical properties, in particular, with the best impact resistance for a non-flexible filament. However, it fails when it concerns layer adhesion.

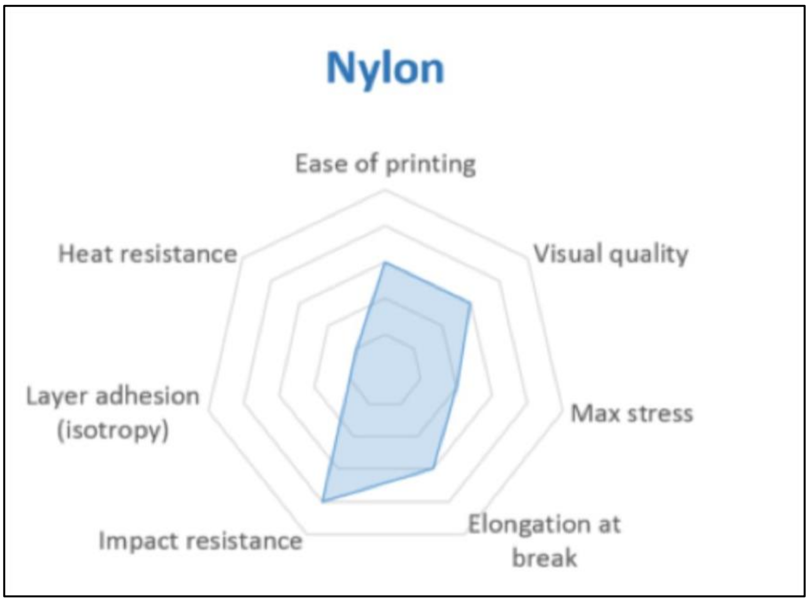

Figure 10 - Nylon spider web chart[15].

Table 4 - Nylon pros and cons[15].

Advantages	Disadvantages
Good chemical resistance	Absorbs moisture
High strength	Potentially high fume emissions

- TPU (Thermoplastic polyurethane)

TPU's most common use is for flexile applications however his good impact resistance can be very good for other applications.

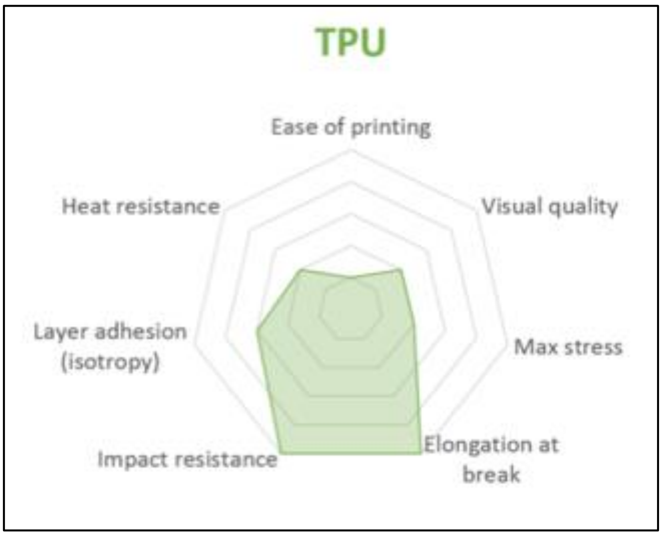

Figure 11 - TPU spider web chart[15].

Table 5 - TPU pros and cons[15].

Advantages	Disadvantages
Good abrasion resistance	Difficult to post process
Good resistance to oil and grease	Can´t be glued easily

- PC (Polycarbonate)

PC is the strongest polymer among the most used ones for 3D printing purposes.

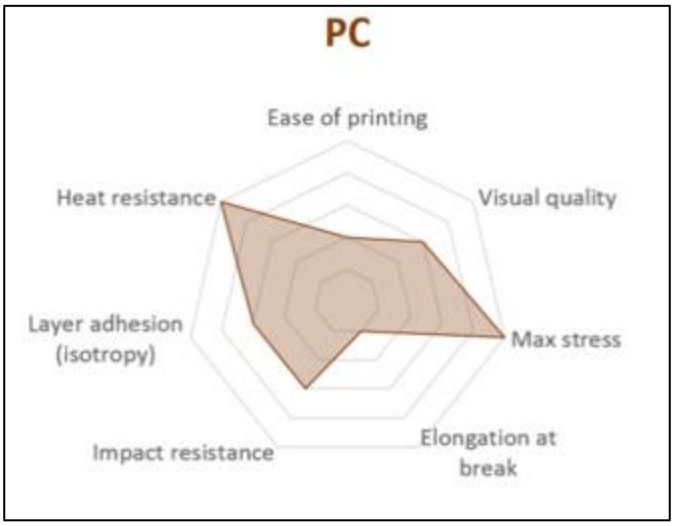

Figure 12 - PC spider web chart[15].

Table 6 - PC pros and cons[15].

Advantages	Disadvantages
Can be sterilized	UV sensitive
Easy to post-process (sanding)	

3.2. Metals

Metal 3D printing exists for a while now, but its popularity only recently started to emerge.

The advances on 3DP techniques and the research made on the material filed as been exponentially growing leading to shorter building periods as well as parts with better properties for the industry it is destined to[16].

3.2.1. Properties

The 3D printing of metals technique is of pored bed fusion meaning that the raw material come in the form of metal powder and then it is melted into the end part. The main processes for metal are direct metal laser sintering (DMLS) and selective laser melting (SLM). To obtain the powder, manufacturers use processes like gas or plasma atomization. By varying process' parameters like gas pressure, melt properties, nozzle design, and gas-to-metal ratio will influence the size of particles produced by gas atomization.

Figure 13 - Metal powder samples[17].

It is very important to ensure material flow and packing density, spherical metal particles of similar size, furthermore, the obtaining process of the powders aims to hence the development of melt pools and microscopic homogeneity. A misjudge on these could bring mechanical problems to the ended part as inconsistent bulk density, increased defects, poor surface finish among others[16][18].

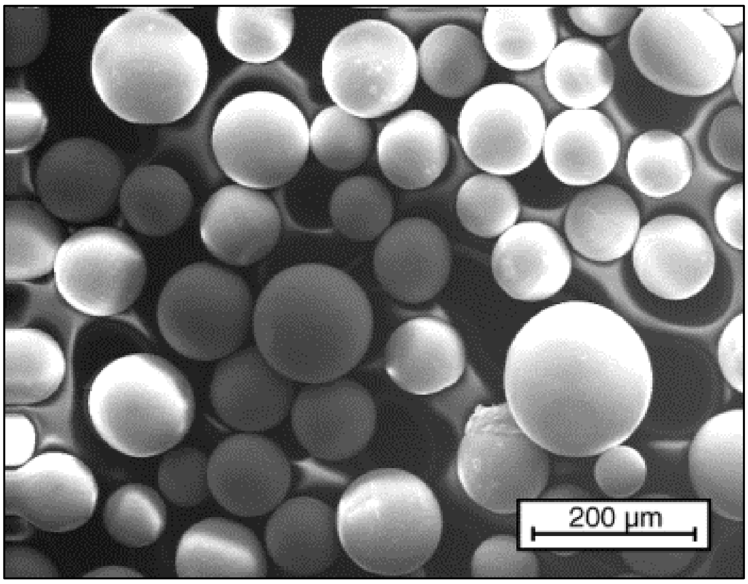

Figure 14 - Atomized, spherical titanium metal powder[19].

So, it is key to obtain a spherical morphology on the metal powder along with high density which confer good flow properties. And for this, at the end of confession, are accessed for size distributions, chemical composition and mechanical properties[18].

Properties end up depending on the end use of the component at hand. Basing on that grain size and the metal itself are chosen for each part's end purpose. Mainly, the metals used for 3D printing are: Stainless-steel, aluminium alloys, titanium alloys, cobalt chrome alloys, nickel-based alloys among others. These powders are between 10-50 microns[20].

Table 7 – Metal alloys used in AM [21].

	Material	DIN
Aluminium Alloys	AlSi10Mg	3.2381
	AlSi7Mg	3.2371
	AlSi12	3.3581
Cobalt Based Alloys	ASTM F75	2.4723
	CoCrWC	
Tool Steels	AISI 420	1.2083
	Marage 300	1.2709
	H13	1.2344
	AISI D2	1.2379
	AISI A2	1.2363
	AISI S7	1.2357
Nickel Based Alloys	Inconel 718	2.4668
	Inconel 625	2.4856
	Inconel 713	2.4670
	Inconel 738	
	Hastelloy X	2.4665

	Material	DIN
Stainless Steels	SS 304	1.4301
	SS 316 L	1.4404
	SS 410	1.4006
	SS 440	1.4110
	15-5 PH	1.4540
	17-4 PH	1.4542
Titanium Alloys	Titanium Grade 2	3.7035
	Ti6Al4V	3.7165
	Ti6Al4V ELI	3.7165 ELI
	TiAl6Nb7	
Precious Metal Alloys	Jewellery Gold	18 Carat
	Silver	930 Sterling
Copper Alloys	CC 480 K	2.1050

From a chemistry point of view, the powder must correspond with the correct type of alloy of the specified material and an assessment and control of the interstitial elements present such as oxygen and hydrogen that impact the properties of the finishing part. Furthermore, metal powders for AM must contain any type of contamination because contamination levels of a few parts per million mean a lot to the overall end quality.

It is not also their chemical but also their mechanical properties that will determine the end properties. Key bulk properties as packing density and flowability, as described above, are key factors. Powders with a high density are associated with the production of components with less flaws and consistent quality. On the other hand, flowability is more associated with process efficiency. These two properties are directly influenced by particle size and shape such as, stiffness, porosity, surface texture, density and electrostatic charge[21].

3.2.2. Advantages and disadvantages

Stainless steel combines good mechanical properties such as tensile strength, hardness, formability and impact resistance. All of which are good for automotive, industrial, food and medical applications. They can be turned into spar or functional parts and come in small series of end product [22][23].

One of these steels is the Stainless Steel PH1 that combines a good corrosion resistance as well as mechanical properties making if a good fit for the biomedical, aerospace and motorsport industries. It is also magnetic[24].

One variety of used stain steels on the industries are maraging like the MS1 used for functional prototypes, injection molds and others in the injection moulding sector as well as on the precision and mechanical parts one. It presents exquisite mechanical properties, is easily machinable, magnetic and fit for post-treatment[22][23].

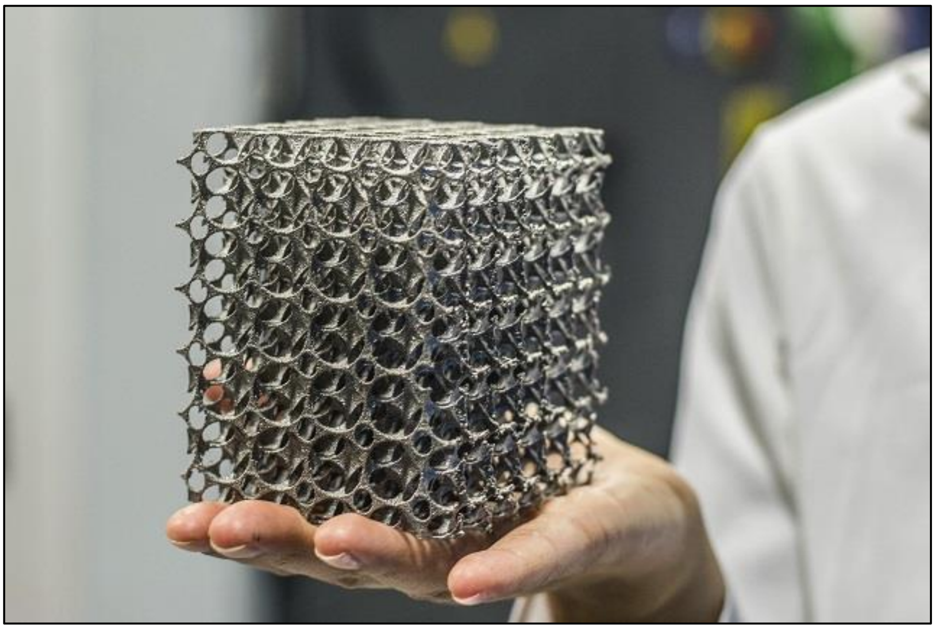

Figure 15 - Stainless steel complex 3D printed part [25].

Another application of a stain steel part is the food industry. Stainless steel 316L (low-carbon) is ideal to be used in food and chemical processing because of its high corrosion resistance. Besides this, the Stainless steel 17-4PH is used to fabricate functional prototypes and automotive and industrial parts. We see here the wide application of the Stainless steel.

Aluminium alloys present a high strength-to-weight ratio making it perfect for aerospace and automotive applications for thin metal parts and others. Besides, its good dynamic properties make it suitable to produce parts further to be subject to high loads. They are possible to be post-treated, present good resistance to metal fatigue and corrosion as well as a good combination of thermal properties[22][26].

As for aluminium alloys powders, they are more advantageous than other types of powders because they offer better build rates and excellent fusion properties making it well-suited for 3D printing[22].

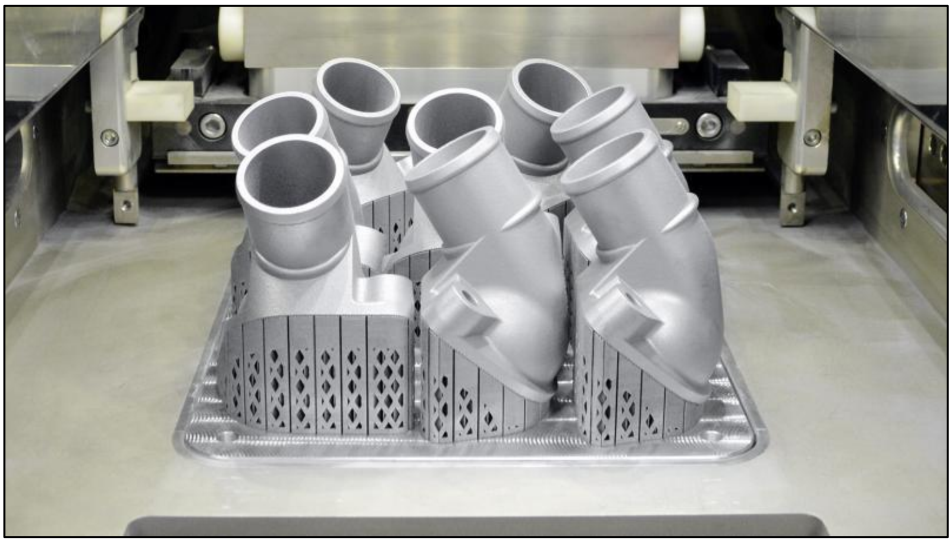

Figure 16 - Mercedes-Benz part made from aluminium 3D Printing[27].

As an example of the wide range and important applications of aluminium, we have AlSi10Mg that combines high thermal and electrical conductivity is suitable for aerospace and automotive applications while ALSi12 is used on the medical sector. More aluminium alloys are being discovered to be compatible with the 3D printing technology meaning that more end use for aluminium alloy parts are yet to be discovered[22].

Titanium alloys are widely used in the industry. Mainly, parts built by it are for the medical sector, for mechanical parts and aeronautics. One of its notorious applications is to produce high-performance race engine parts like gearboxes. Besides this, titanium alloys are suitable for medical purposes when direct contact between bone or tissue with metal is required.

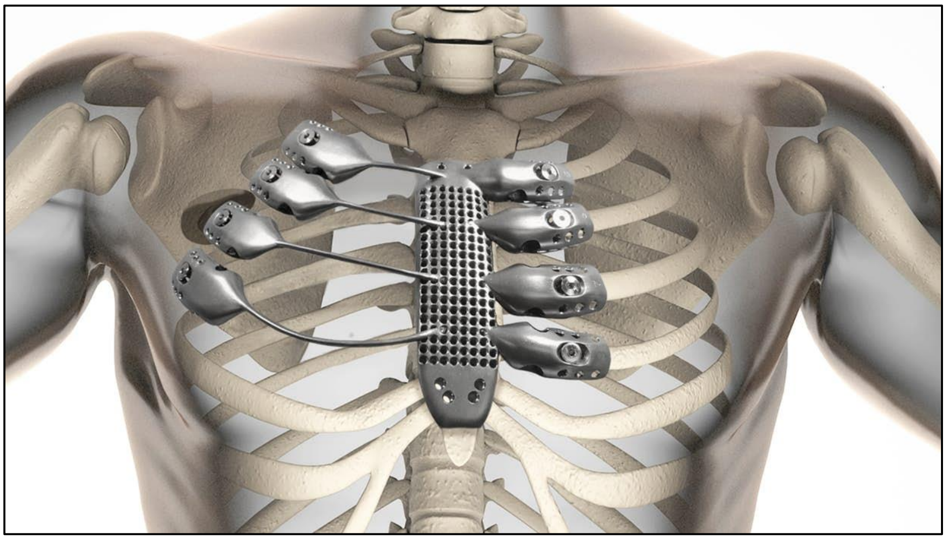

Figure 17 - Medical 3D printed part made out of titanium [28].

Two popular titanium alloys that are popular on the AM industry are Ti6Al4V and Ti6Al4V (ELI) due to their mechanical properties. The first one is able to maintain its tensile strength at super high temperatures. It is a high-strength metal with excellent corrosion resistance as well as it is weldable and heat-treatable.

Figure 18 - 3D printed compressor blades [29].

The Ti6Al4V (ELI), because it contains less hydrogen, oxygen iron and carbon, can have better ductility and fracture resistance. It is usually used in offshore oil and gas extraction applications where its corrosion resistance in salt water is a key factor for its good performance [22][29].

4. Processes

4.1. Introduction to 3D process

Many are the processes that one can go to when in need for a 3D printed part. Some of these processes have been going on for a while and some new to the industry world.

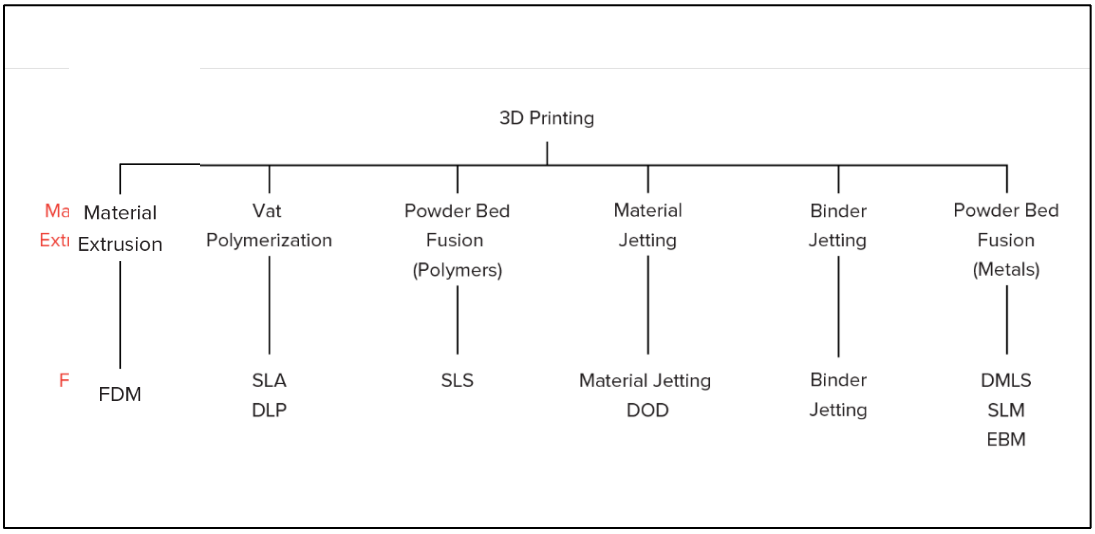

Figure 19 - 3D Printing different processes[30].

In this work we've decided to focus on the most essential.

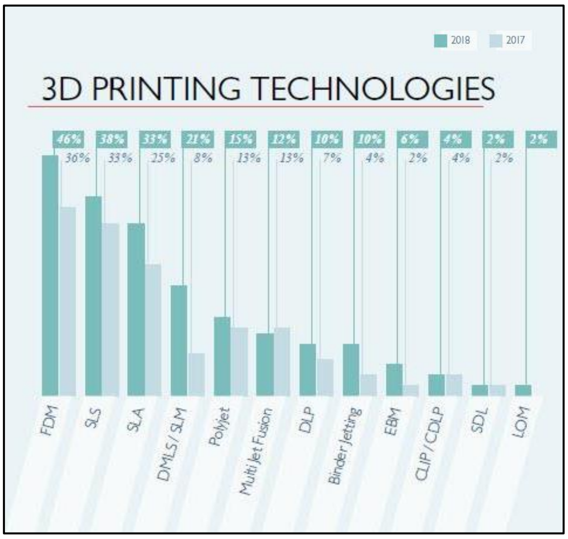

Figure 20 - Most common processes of 3DP in 2018 and 2017[31].

It is to say that one is no better than the other. Each one of them is good at their own way, it is up to the operator to be able to choose which of the processes best provides the final piece with the structural, visual, and mechanical properties suited for the posterior work it will have to endure.

Although different, AM processes consist on the layer-by-layer addition off material in order to build the final desired part. For that, support structures are added to the design in some areas, either critical or because of its desired geometry. Furthermore, a post-process is sometimes needed for the enhancement of the piece.

4.2. Fused Deposition Modelling

Fused Deposition Modelling (FDM) in 3DP is the most recognized process, at a consumer's level, in the world of 3DP. It was introduced in the late 1980's. This simple technic consists on a filament coil, that is used as printing material, being melted and extruded via an extruder and deposited layer by layer on the printing plate.

The material starts by being heated up until around 200ºC to be able to melt the working material. Then it is deposited into successive layers until the product is completed. To note the full ability of the machine to move freely along the X, Y and Z axis[32].

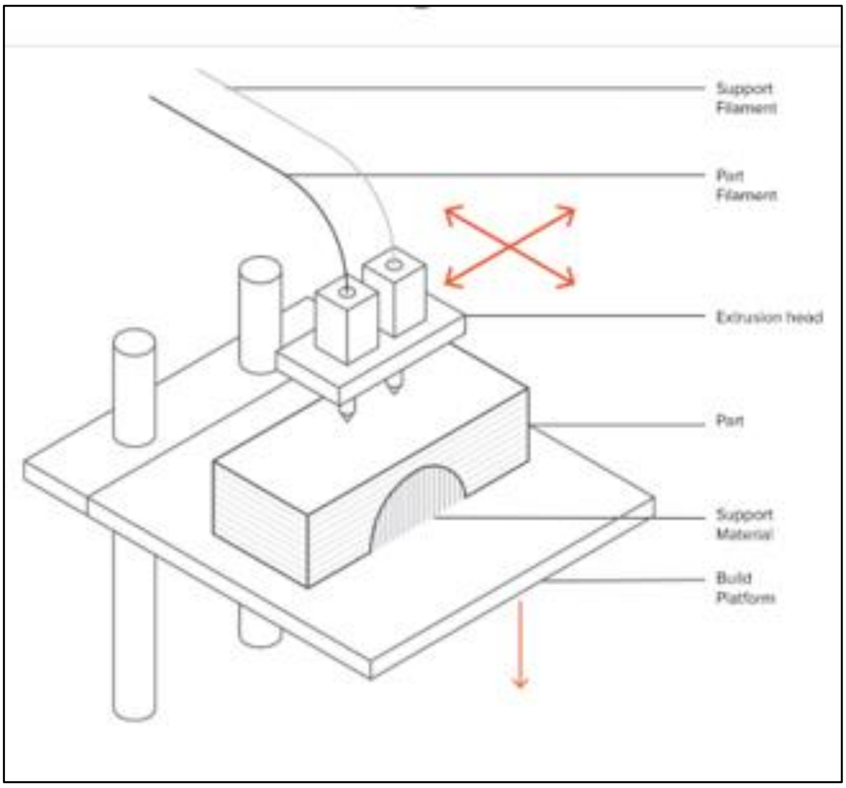

Figure 21 - FDM 3D printer schematic[30].

The typical layer height for this process varies between 50 and 400 micros being 200 micros the most commonly used, however, this technique presents one of the lowest surface qualities, so, a post treatment polishing is needed.

One of the most common defects in FDM is warping. It happens when the extruded material cools and the parts dimensions decrease. This happens differently along the part because not all of the part has the same building speed. Because of warping, internal stresses are generated and it can compromise the part.

To best manage this, the designer has several aspects to pay attention to:

- ✓ Large flat areas are more prone to suffer warping and, therefore, should be avoided;
- ✓ Sharp corners warp more often than rounded shapes, so, adding fillets to the design is of good practice;
- ✓ The use of different materials can also help fighting warping. ABS is generally more sensitive to this effect when compared to PLA or PETG due to its higher glass transition temperature and relatively high coefficient of thermal expansion[30].

Another key aspect to take into consideration when dealing with FDM is the layer adhesion. FDM parts are anisotropic. Their Z-axis strength is always smaller than the one felt on the XY-plane. So, it is important to keep part orientation when designing parts for FDM.

Figure 22 - Surface of a 3D printed object[30].

Because of the constant pressing of the downwards material when a new layer is added, the edge's surface gets shaped into an oval form. This means that FDM parts will always have wavy surfaces. So, a post-process is required to these parts.

It is important to understand that the surface finishing when it concerns rugosity and irregularities is very important for pieces that will undergo some certain type of contact with fluids. For example, for airplane purposes or automobile purposes or air vents. This rugosity will affect aerodynamics and the overall flow of the fluid generating a turbulence regimen on that brings unwanted consequences to the matter at hand.

A support structure is needed when creating geometries with overhangs, the melted thermoplastic cannot be deposited in thin air. These parts will be of lower surface quality, so, parts printed by FDM must be design in order to minimize the need for support.

The main materials on FDM depend on the end need a part will have[30].

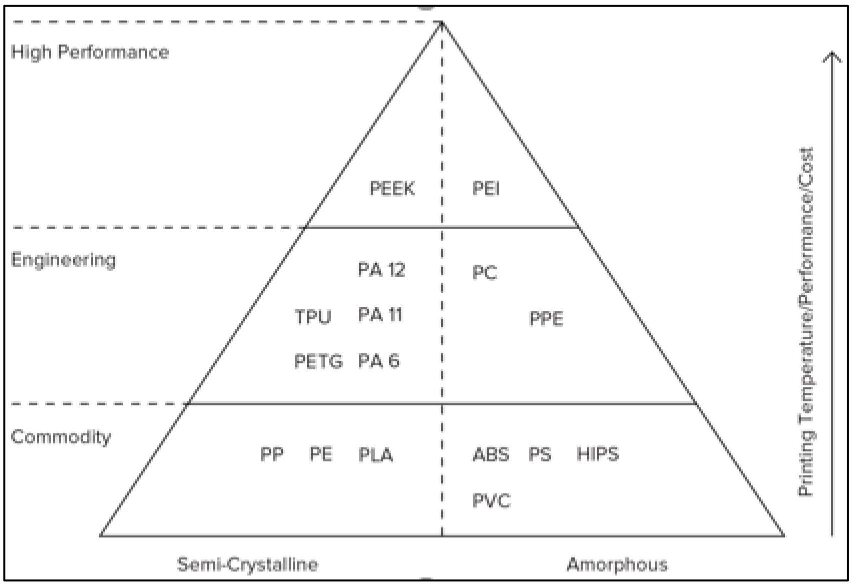

Figure 23 - Thermoplastic materials pyramid available in FDM[30].

As post-processing an FDM part, one can use several techniques such as Sanding and polishing, priming and painting, cold welding, vapor smoothing, epoxy coating and metal plating.

Table 8 - FDM synthesis[30].

	Fused Deposition Modelling (FDM)
Materials	Thermoplastics (PLA, ABS, PETG, PC, PEI)
Dimensional accuracy	± 0.5% (lower limit ± 0.5mm) – desktop ± 0.15% (lower limit ± 0.2mm) – industrial
Typical build size	200 x 200 x 200 mm – desktop 1000 x 1000 x 1000 mm – industrial
Common layer height	50 to 400 micros
Support	Not always required (dissolvable available)

4.3. Stereolithography

Stereolithography, also known as SLA (Stereolithography Apparatus) is an addictive manufacturing technique that consists on photo-polymerizing a UV-sensitive resin, to produce 3D models. So far, it produces pieces with one of the best finishing surfaces among others 3D technologies.

Looking back, we can consider this process to be the founder of 3D printing as its first patent application was filed in 1984 and then commercialized in 1984[33].

After having sent the 3D digital file required via CAD, normally a STL file, to the printer, the additive manufacturing process begins.

A mobile platform along the Z axis goes down (top-down SLA printer) one layer every time the laser beam covers the entire surface of liquid resin in accordance to the provided 3D model. By doing this, the UV laser is curing and solidifying the photopolymer resin making the desired layer. This process is repeated until we obtain the totality of the piece.

This whole process can be done upside down where the platform begins submerged on the resin with an upwards Z movement (bottom-up SLA printer).

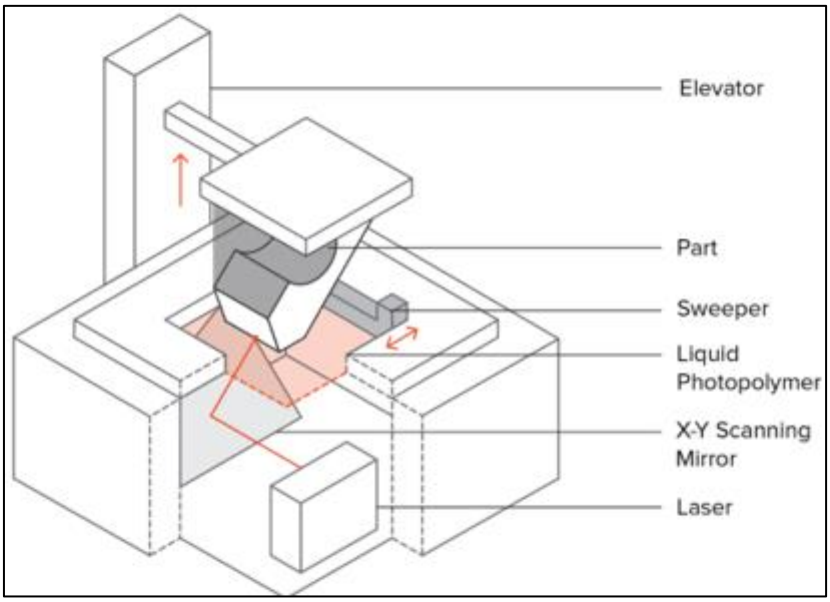

Figure 24 - SLA bottom-up 3D printer schematic[34].

Once the piece is completed and, unlike other techniques, a UV post-treatment is required to maximize the strength of the material. This technique offers a slightly vitreous surface finish but still provides, in general, a better finishing than processes such as FDM or SLS. In the end, the different layers of printing are barely visible, however, a colour change can be recognized[33].

This is a relatively fast process that, depending on the quality of the printer at hand, it is possible to produce immediate functional parts. However, a support structure is always required on this process. These are printed on the same material as the part itself and it is vital that the critical areas of the part don’t get in contact with the support structure. For this, part orientation is essential[34].

For the support structure in SLA top-down printers, the requirements for it are similar to the ones described on the FDM process. They are required to print overhangs and bridges. On bottom-up SLA printers, besides all the supports needed for overhangs and bridges, parts need to be built with some angle so that, when on the peeling process, the forces applied to the part doesn’t make it detach from the building surface. Because of this, the reduction of support for these printers is not a primary concern as the overall accomplishment of the part is the main deal[34].

Figure 25 - Part orientation on a top-down SLA printer (on the left) and a bottom-up SLA printer (on the right)[34].

The main defect on the SLA process is Curling which is similar to what happens in FDM with the warping of the parts. During the solidification process, resin shrinks and, if significant, it generates internal stresses that compromise the integrity of the part.

To enhance the part's mechanical properties, SLA parts must be post-cured. Parts are placed in a cure box under intense UV light. By doing so, their hardness and temperature resistance suffers a great improvement, however, parts become more brittle. For a better surface finish, parts can be post-processed by being submitted to sanding and polishing, spray coating among others[34].

4.4. Selective Laser Sintering

The technology used on this process consists on powered bed fusion. It is super effective on the production of multiple pieces.

After the CAD file is sent to the printer, a solid part is produced from a powder that lies on a container box. A thermal source heats up the powder that takes a solid shape, after all the layer is completed a piston goes down as much as the thickness of the layer and another goes up pushing more material into a roller that spreads it onto the working base. These steps are then repeated until the piece is completed[35].

Most SLS printers have an accuracy up to 100 microns.

When the piece is done, sometime needs to be taken so the material cools down, if not, the part produced can either warp or shrink leading to the unwanted generation of internal stresses. Once it is cooled down (process that can last up to 12 hours), the unsintered material is removed with compressed air where around 50% of it is recyclable to then be reused [36].

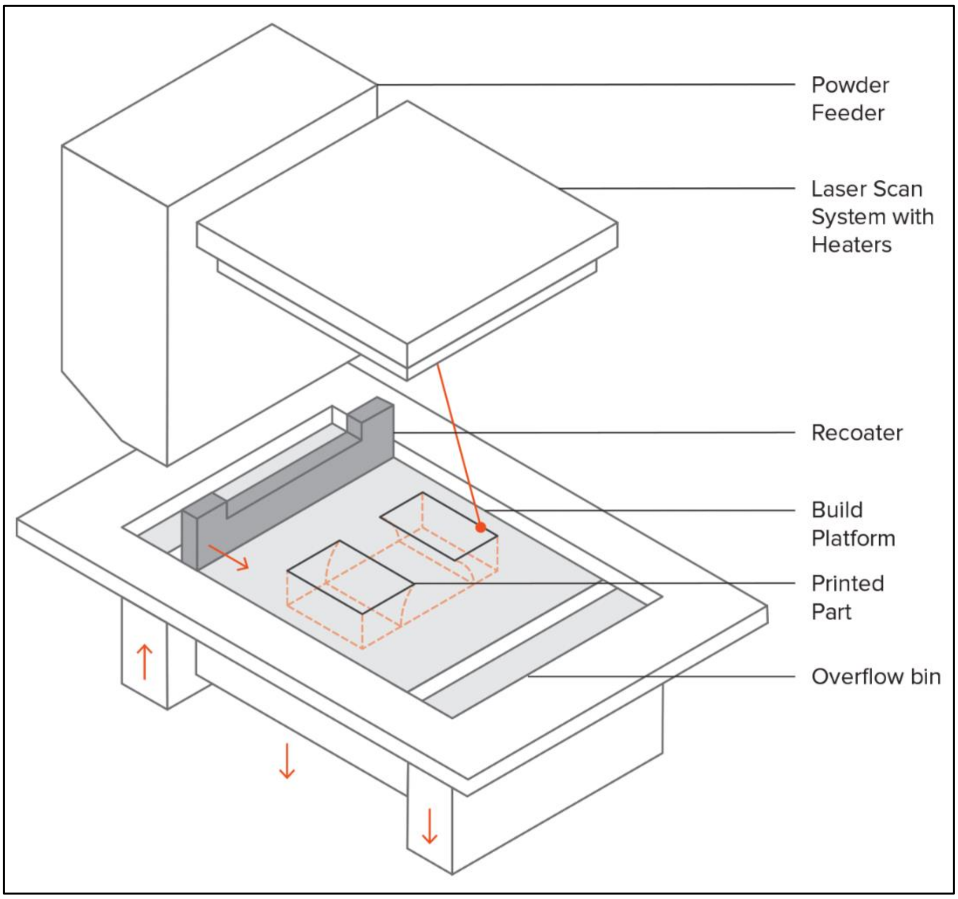

Figure 26 - SLS 3D printer schematic[36].

It is worth noting that different powders will affect the finishing surfaces of the pieces where finer ones allow for smoother surfaces but take the downside of creating problems during the recoating stage of the process.

The uses of this process are wide such as automotive, biomedical engineering and aerospace where it produces pieces with materials such as metals (such as titanium, steel, alloys) and polymers[35].

Because of the high accuracy of SLS printing, it is suited for strong and functional parts without the need to add any support materials while the process is being conducted due to the accumulated uninterred material. On the downside, it is a very expensive industrial process regarding machines and material (being PA or polyamide the most used). Furthermore, let's not forget the necessary cooling time that affects negatively the pieces lead time.

As for layer adhesion on SLS parts, it is excellent meaning that they almost have isotropic mechanical properties however, their internal porosity is up to 30% meaning that, even though they have excellent tensile strength and modulus, they are brittle and, if the part at hand is going to be submitted to humid environments, they will require special post-processing[36].

4.5. Processes Comparison

FDM provides the lowest resolution and accuracy to the pieces when compared to SLS and SLA. So, to do more complex parts, this may not be the best option. However, some chemical treatments and mechanical polishing processes can be applied to pieces obtained from FDM in order to have a higher quality finish.

SLA brings up the best qualities in pieces. It has the highest resolution and accuracy providing the smoothest surface finishes of all 3D printing technologies that involve plastics. Because of this, manufactures have put in a lot of work into creating resin formulations to use in SLA so to be able to have optical, thermal and mechanical properties to match the standard ones you see in any engineering and industrial thermoplastic.

SLS is a popular choice among engineers due to the process's high productivity as well as the low cost per part and the good mechanical properties materials involved in this process present, mainly nylon[37].

	Fused Deposition Modeling (FDM)	Stereolithography (SLA)	Selective Laser Sintering (SLS)
Resolution	★★☆☆☆	★★★★★	★★★★☆
Accuracy	★★★★☆	★★★★★	★★★★★
Surface Finish	★★☆☆☆	★★★★★	★★★★☆
Throughput	★★★★☆	★★★★☆	★★★★★
Complex Designs	★★★☆☆	★★★★☆	★★★★★
Ease of Use	★★★★★	★★★★★	★★★★☆

Figure 27 – Processes comparison[37].

4.6. Process Challenges

With the continuous widespread use of AM and even more set of applications, parameters for the process itself and the product become stricter. Rapid prototype, term many times used to refer to AM, can be misleading in what concerns building speed. It is obvious the facilitations it brings to the design of new products and product development itself where the time spent on the creation of a functional prototype is by far much more reduced when compared with traditional technologies. However, in mass production old techniques such as injection molding are still faster than AM and many times preferred. Nevertheless, the benefits it brings are obvious and sometimes AM is preferred when higher process flexibility is needed.

The referred stricter parameters being required by manufactures/consumers extend to the mechanical properties of the parts created by AM. These parts are expected to either match or surpass the products being produced from subtractive and formative technologies. They are, in fact, of inferior quality when compared to parts produced by more traditional processes. Depending on the cause of it, many times this reason lies on the short range of choice for the materials being used or to the inevitable porosity of parts derived from the power bed fusion technique. Besides that, due to the layer-by-layer type of construction, properties become anisotropic throughout the piece, with the boundary between adjacent layers defining the part's weakest spots with the accumulation of residual stresses[14].

A study conducted by Kotlinski on the analysis of the mechanical properties of commercialized AM materials and techniques found the anisotropy to be worst for LOM (Laminated object manufacturing) and least critical by using SLS. Furthermore, for the FDM process, both anisotropy and mechanical properties were found to be very dependent on the material and process parameters.

Spatial resolution is another major concern for any AM process. It is influenced both by the AM technique itself and by the processed material it uses. No need to say that insufficient resolution brings defects in the quality and the object's functionality even considering CAD file's high quality a certain level of irregularities is supposed to be expected. That is accentuated by the stair step surfaces originated from the layer-by-layer type of process AM is based on.

For the resolution problem, a lot of studies are continuously being made with the goal of search for better materials and AM techniques. Apart from that, the layer thickness is essential to diminish the mentioned stair step surface. It was until 2015 when a process called continuous liquid interface production (CLIP, will be discussed in another section) was invented in order to eliminate the need for a stepwise process[14].

There are also production uncertainties to be aware of. In traditional processes that start with a block of material that is constantly being cut away, the finishing properties of the piece will be the ones the initial material had. Where in 3D printing, it doesn't happen. Many are the parameters that influence the end piece's properties. The same design can have different properties if it is done on two different printers, furthermore, the environmental conditions where the piece is being done also influences its final properties or even the operator itself. So, parameter as humidity or temperature and many others that aren't specified in a design file are to take into account. This means that critical parts need to be carefully checked to ensure structural integrity. It can be done through ultrasound but not for all metals, other way is by Industrial computerised tomography scanning which is slow and expensive and doesn't work for complex shapes that you might have, considering you are recurring to AM to build the piece at hand [38].

4.7. Hybrid manufacturing

Hybrid manufacturing is a combination of additive process (AM) and subtractive processes, such as milling. The crucial qualifier for hybrid manufacturing is that both processes can occur in the same machine, combining the advantages of each one [39].

Hybrid manufacturing made its first commercial appearance in the early 2000's via Laser-Powder Deposition in a CNC machine. In the following years this technology grew up, but only in 2010 with the big development of 3D printing, hybrid manufacturing had the help to flourish. At this time, the cost of printing lasers had dropped to 85.000 €, making it possible to couple with a large CNC machine tool. Also, at that time, 3D printing metal machines were being delivered around 700.000 to 1.300.000 €, making hybrid manufacturing an ideal alternative especially for large parts [40].

Machines that combine not only subtractive processes, but also additive manufacturing can make the process more precise. As an example, the use of a planar milling at the end of each additive layer, allow a smooth planar surface where a new layer is then added, preventing and eliminating accumulative effects from errors in droplet deposition height [41].

Figure 28 - Hybrid Machine (HYBRID Manufacturing Technologies ®) [42].

As an example of this is the stratoconception approach, where the original CAD models are divided into thick machinable layers. Once these layers are machined, they are bonded together to form the complete solid part. This approach works very well for very large parts that may have features that would be difficult to machine using a multi-axis machining center due to the accessibility of the tool. This approach can be applied to foam, wood-based materials and metal [41]

Hybrid manufacturing is now a common process, recognized in industry for combining additive and subtractive process. Since 2013, the number of machines producers offering this type of machines, went from zero to dozens [40].

4.8. Multimaterial 3DP

The printing of objects with several materials is key to make the additive manufacturing technique be at its full potential and way over other current manufacturing methods. Despite the many advantages that will be explained below, it is important to take into account the pros and cons of these technique has it can lead to the waste of more material than intended [43].

Once mastered, multi-material 3D printing has the potential to eliminate the need for assembly of parts, where besides time it also requires operators to do so, it has, as well, the potential to eliminate post-processing stages such as colouring, can as well boost the design efficiency on multifunctional objects and helps reduce manufacturing costs and time [43].

With this technique it is easy to print with 2 materials, but the struggle still continues when more materials are required. Some 3D printers can even print up to 4 materials. One more advantage to this process relies on the capability of, when printing a component, use water soluble material for the support structure, reducing the costs and difficultness of having to have an operator dealing with the separation of the part and this structure. However, the cost of these materials is very high, and they will go to waste once they are dissolved in water. What some companies have been doing is to only use the soluble on the interface support structure – piece, saving a lot on the overall material cost [44].

There are several ways in which one can print with multi-material.

The simplest way involves, by hand, to switch out the filaments being used at any point you want and then simply either change material or to a different filament color. The limitations of this process are big in what concerns costs and time, so it is not used at an industry level due to this stated and problems with precision and layer adhesion [43].

Another potential method is to have a dual extrusion where you can produce parts with up to two colors or materials. What is normally done is to use one of the extruders to print soluble supports for a later easier part disassembly. However, this process has some limitations because by having two extruders instead of one, the main one, on a single extruder printer, doesn't have as much available area to print, furthermore, there is a higher chance of oozing and stringing alongside with layer-shifting defects [43].

You can also turn a FDM printing machine into a multi-material printer by adding a device that manages filament switching operations while using one single extruder. One of the best options to go to is the Palette 2 Pro recognized by the Mosaic Manufacturing. The good thing about this device is that it merges the filaments and fuses them so at the time of extrusion the right material is being the one set into place. You can combine up to four filaments. When dealing with a multi-material part, a purge block is used where, when changing between materials, it automatically pours some of the old material out, cleaning the extruder, and then begins adding the new material. This explains the more waste of material mentioned on top which can be inconvenient when dealing with expensive materials [43].

For an industrial use, the ProJet MJP 5600 uses VisiJet Multi-material composites that allow you to blend together rigid and flexible materials [43].

Figure 29 - Multimaterial 3D printer [44]

The printer at hand precisely mixes polymers to achieve superior mechanical properties as well as customized mechanical and performance properties. By doing so you can use the strong points of multi-materials in order to assemble the part required offering more range of applications [44].

5. Importance and challenges of AM in industry

This chapter will present current solutions where industries are applying AM into their value chain. The industries under scope are the following: automobile, aeronautical and medical devices sector.

5.1. AM in Automotive industry

It's not unanimous about how AM is revolutionizing manufacturing, including automotive manufacturing [45], but many studies refer improvements and a significant changeover in this sector, caused by this technology [8] [46].

AM has been evolving over the past 30 years and 36% of companies are already applying or intend to apply AM, in which, the automobile sector among others, are the more mature sectors where AM is leveraging business [8].

The automotive industry is under significant price and cost pressure. Tier 1 and tier 2 suppliers, which supply components directly to the original equipment manufacturer (OEM), are chasing operational excellence to remain competitive. Profit margins for component parts are tighter than ever before. Furthermore, the service agreements between component suppliers and OEMs require spare parts to be on inventory for several decades. On the other side, consumers demand customization. This adds complexity into the production, as low-volume and high-variation parts can bring inefficiencies into the system [13].

In one hand, AM can produce components with fewer design restrictions compared to the more traditional process. On the other hand, can be the driver of supply chain transformation, by eliminating the need for new tooling and directly producing final parts [46].

AM is especially attractive to the automotive industry, because in some cases it can produce what traditional manufacturing methods cannot. AM can thereby add most value in the realization of product concepts. With 3DP, lightweight car components can be produced, which could lead to car weight reduction, improvement of car performance and better fuel economy [46].

As an example, *Local Motors®* was the first company to 3D print a car, with over 75% of the pieces printed. This is also important because of the fact that they reduced the amount of pieces of a car, more precisely, from thousands to a simple dozens of pieces, which decreases the complexity of mounting a car, and increases the longevity of it [47].

Figure 30 - Strati car created by Local Motor® [47].

Another example of 3DP application happen when *BMW* ® developed a one piece, light-metal, 3D-printed water pump wheel to replace. The high-precision component is part of one of BMW's DTM race cars and is subjected to high stresses. The water wheel consists of an aluminium alloy. The pump is a metal part built using selective laser melting (SLM), where 0.05 millimeter layers of aluminium alloy powder are built up on a processing plate to form a durable, high-precision component [48]

Figure 31 - Water Wheel created by BMW ®

5.1.1. Challenges

The challenges of AM's future applications in the automotive industry will depend mostly on how AM technology evolves over the years.

On one side, AM applications have been restricted to the limitations on materials that can be used. Due to this limitation, researchers from Warwick University have been working on a low-cost composite material to build electronic components [49].

An advanced material of note is carbon fibre, that is used to make lightweight auto components such as fenders, car roofs, and windshield frames though conventional techniques, AM, too, is beginning to take advantage of this material with the lunch of the first commercial AM device that can use carbon fibre. [50].

Other emerging materials for 3DP are nanomaterials, that promote the decrease of sintering temperatures and improving mechanical and electrical properties. The homogeneity of products can also be improved, when using these materials. Nanocomposites have attracted the attention of the industries due to its properties, such as good thermal conductivity, enhanced performance, excellent strength and lightweight, which are fundamental for the industry competitiveness in automobile sector[51].

Most of components manufactured through AM require postprocessing, which involves removing unused material, improving surface finishing. In some components, because of it's complexity it may become necessary to improve postprocessing quality and reliability for AM to be used in large scale, like the production of engine manifolds [46].

Profitability in the automotive industry is driven by volume. In 2013, 86 million automobiles were produced globally, and given the enormous volumes, the low production speed of AM is a significant impediment to its wider adoption for direct part manufacturing [46]. This has been an important focus in recent years but need more solid results to breakthroughs this limitation.

Manufacturing large components, such as body panels are still a big challenge, because nowadays these pieces can be produced by AM technology, but they need welding or mechanical joining. To over-come this limitation low-cost AM technologies that can support larger build sizes for metal parts must be developed. There is some significant research about this topic, and important steps were made, with *Mammoth* technology, despite the fact this only could print panels of plastic [46].

Using the *Mammoth* stereolithography machine it is possible to manufacture parts up to 2100x680x800 mm. With this machine, *Formula Group T* team working in collaboration with engineers at *Materialise* developed the car body in just three weeks, in 2012 [52].

Figure 32 - The machine Mammoth with printed car body (left) and the world's first 3D printed race car (right) [52].

The final challenges that AM faces in automobile sector are with talent shortage and intellectual property concerns. In one hand, a new technology needs specific training, like CAD skills, AM machine making, operation, maintenance, analysis of finishing; and supply chain. On the other hand, AM products can't be copyrighted but must be patented based on obvious differentiation.

5.2. AM in A&D industry

The aerospace and defence (A&D) industry is a great example of the AM utilization, with a clear value proposition and the ability to create parts that are stronger and lighter than parts made using traditional manufacturing [53].

AM is relatively widespread in A&D industry cause it provides the flexibility to create complex part geometries that are difficult to build using traditional manufacturing, unlocking the possibility to build pieces with internal cavities, that help to reduce part's weight without compromising the mechanical performance [54].

Furthermore, AM machines produce less scrap than traditional machines, a critical attribute when using expensive aerospace materials such as titanium.

Finally, the impact of AM on economies of scale and scope make it a natural fit for A&D, which, in contrast to other mass production industries (p.ex.: automotive), is largely oriented toward customized production [54].

Bellow we can see some advantages that 3DP brought to the A&D industry:

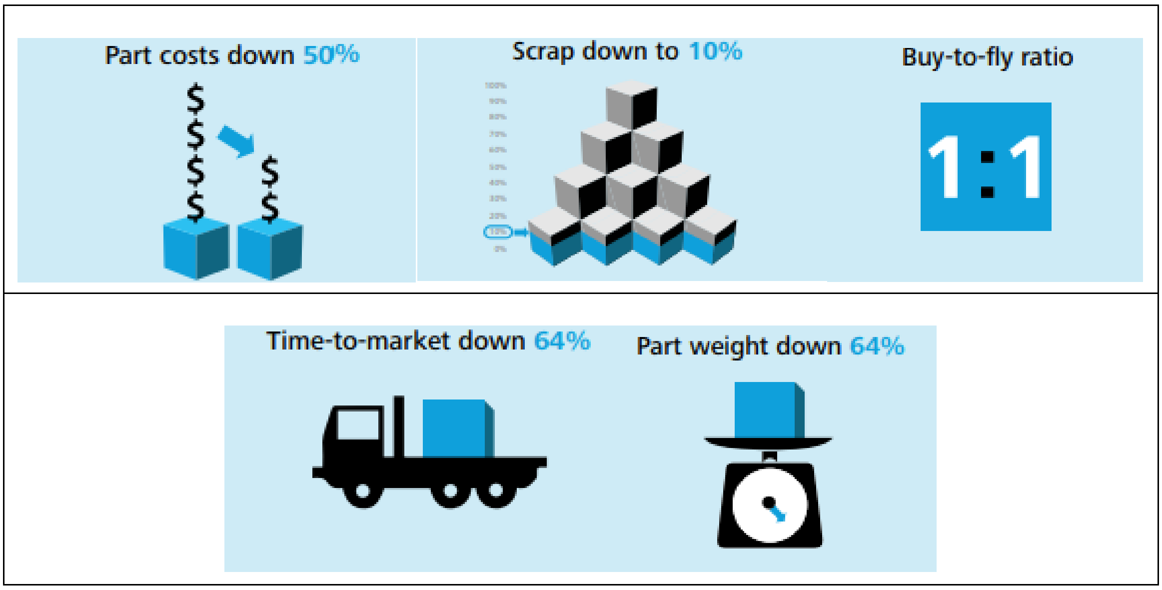

Figure 33 – Examples of benefits of producing different A&D parts [54].

An example of light weighting through 3D printing, happen in January 2015, when *Materialise®* manufactured plastic parts for the A350 XWB which consumes 25% less fuel, due in part to 3D printed parts [55]. This new jet had more than one thousand printed parts, and with a good fuel efficiency compared to the competitors at that time.

Figure 34 - Airbus A350 XWB [56].

Currently, Air ducts, wall panels, seat frameworks and even engine components have all benefited from reduced weight enabled by 3D printing.

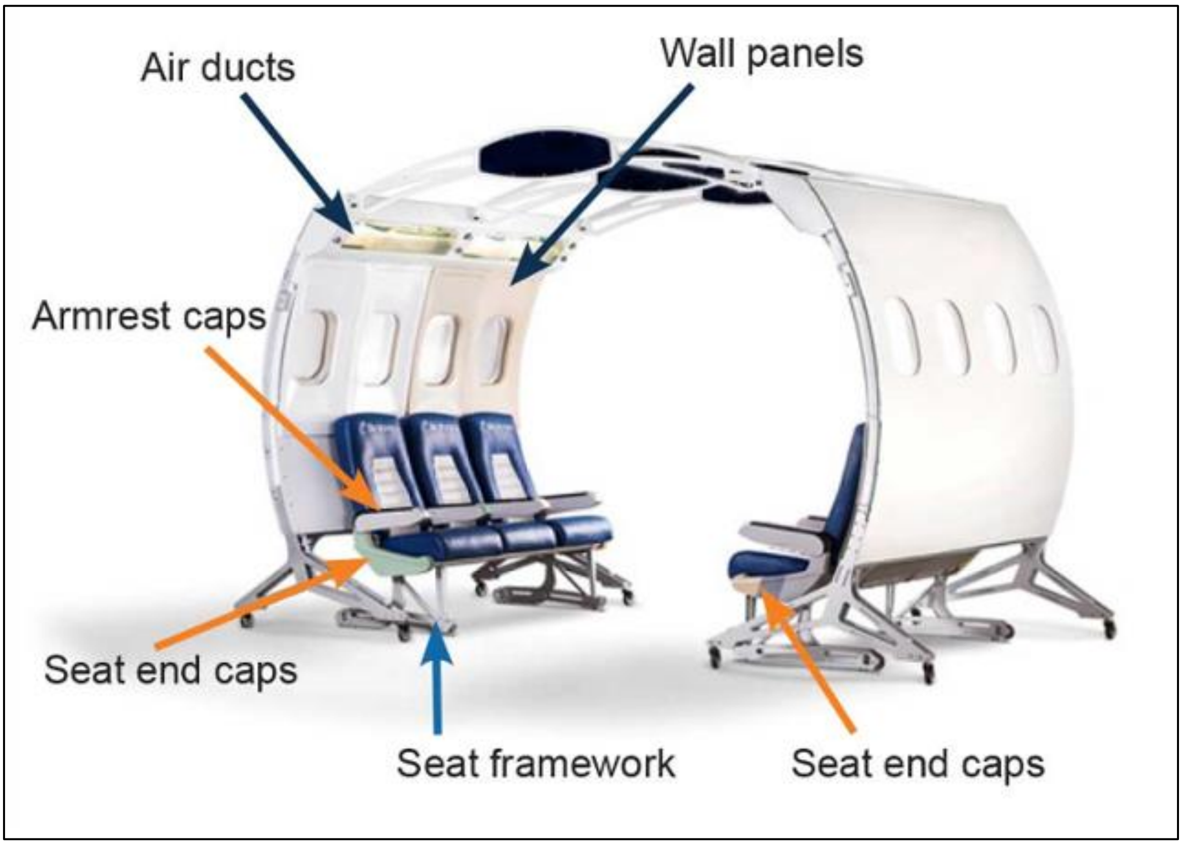

Figure 35 – 3D printable Aircraft components (Airbus) [57].

Materialise is a company like many others (*3D Systems*, *Stratasys*, etc) focused on determining the strength and functional requirements to meet the needs of the highly-regulated aerospace industry. First, the design of light-weight structures, and then the 3D validation is performed for the printing. The unique 3DP allow structures that have the same strength and function with less material, reducing overall weight [55].

Figure 36 - 3D parts printed by Materialise ®, optimized support structure for drone (left) and printed titanium insert for spacecraft (right) [55].

Aerospace parts frequently include internal channels for conformal cooling, internal features, thin walls and complex curved surfaces. 3D printing is capable of manufacturing such feature and moreover it allows the fabrication of highly complex and lightweight structures with high stability [53].

Surface finishing is also critical for the aerospace industry. Some technologies, such as Material Jetting[1], can produce parts with smooth injection-moulding, like finish off-the-printer with little post processing needed.

Summarizing, AM has the potential to revolutionize A&D companies in many ways, such as [54]:

- **Reduced time to market**: By quickly building prototypes with the required fit, form, and functionality, thereby accelerating design cycles, reducing time to market; Research has shown that when A&D companies switch from traditional manufacturing to AM, they could benefit from time savings in prototyping between 43% to 75%;
- **Complex-design tools**: The free-form designs helps in building tooling fixtures that are difficult or impossible to produce with traditional machining techniques;
- **Flexibility of design iterations**: AM offers the flexibility to design and test products as many times as required, helping A&D companies reduce risks and uncertainties and improve product functionality at lower cost;
- **Tooling at lower cost**: An important aspect of AM is that helps to lower the cost of manufacturing tools and fixtures, leading to overall cost savings of 79 percent and lead time reduction of 96 percent compared with traditional tooling.

5.2.1. Challenges

Nowadays AM technology faces some challenges associated with size and scalability, high material costs, narrow range of materials, limited multi-material printing capabilities, and consistency of quality. Once again, like in automotive industry, continued development is required, to overcome these limitations, making easier the adoption of AM in A&D industry.

Bellow will be discussed in detail the challenges that A&D industry, currently faces in terms of:

- Size limitation;
- Scalability limitation;
- Narrow range of materials;

[1] **Material jetting** is the only additive manufacturing technology that can combine different print materials within the same 3D printed model in the same print job [53].

- Limited multimaterial printing capabilities.
- Quality consistency.

AM still underperforms traditional manufacturing, concerning the production of large components. The main producers are focusing their research and development efforts on addressing the size limitations of existing AM systems. *Lockheed Martin* is working with Oak Ridge National Laboratory (ORNL) on a big-area additive manufacturing (BAAM) system in which multiple deposition heads work in coordination to build large parts in an open environment, unconstrained by the typical envelope size.

Figure 37 - Big-area additive manufacturing (BAAM) [58].

One of the challenges of the market are the restriction of the volume of construction and the size of the product. Aircraft is made up of very large components and additive manufacturing is today limited to the volume offered by the 3D printer. Most technologies offer solutions with limited print volume, making 3D printing applicable only to small components. So, we still have this constraint that could slow down the growth of the market

Even if s today's 3D technologies have already made it possible to create large pieces. An example is the fuselage panel created by STELIA Aerospace. As well as companies such as GE, that's already working on expanding the size restraints step by step [59].

Figure 38 - Stela Fuselage printed [59].

Nowadays, most of the A&D companies producing parts by conventional processes as well as the sourcing A&D companies, face the challenge to stock large inventories, and a majority of which may be unused. On the other hand, AM systems may not be able to scale up production when required [54].

AM providers face the production speed very seriously because that will support the needs on mass production industry. There are some solutions to this problem, one is the possibility to produce and unloading of parts happening simultaneously. This approach would help improve AM's scalability.

Another challenge of today's AM companies in A&D are the narrow range of materials and high material cost. AM predominantly uses specific kinds of polymers and metal powder to manufacture A&D parts, and the costs of these materials are much higher compared to the materials used in traditional manufacturing methods [60].

From another point of view, limited multimaterial printing capability is also a big challenge, and currently with few possible solutions at hand. Advances in this area will help designers make a part using different materials with varying properties. For example, one section of an aerospace part can be built from a material with flame retardant properties, while other sections can be made of an extremely lightweight material [60].

Finally, the last challenge presented in this report is the quality consistency, specially the one obtained when producing fully dense metal parts, which the excess of heat lead to stress and voids, particularly on layer boundaries. These challenges can be bypassed by embedding controls within the machines so that in-situ dimensional accuracy in ensured, and by implementing automated inspection in the process of printing the piece, layer by layer.

5.3. AM in MedTech industry

The medical technology industry has been on the forefront of additive manufacturing development and industry consolidation. In 2012, medical applications accounted for 16.4 percent of the total system-related revenue for the AM market, and that's an important fact that explains why AM capabilities are so well aligned to the medical technology segment [61].

As an example, MedTech segment as a geographically widely distribution of population service and even a larger and market of health care consumers [61].

From another point of view, many medical devices like hearing aids, dental crowns, and surgical implants, are produced in small batches, which are preferably produced by common AM systems. Additionally, these products are value-dense, combining relative high value with relatively small volume, and the high level of customization makes AM technology better suited for this custom-fitting products [62].

MedTech industry is also very well founded, by most countries, which is also a point in favour when it comes to invest in new technologies.

Given the strong alignment of AM capabilities with the medical device segment's needs, it is no surprising the big breakthroughs that AM faced [61].

AM in MedTech industry can be organized in several categories, including creation of customized prosthetics, implants, and anatomical models, tissue and organ fabrication; manufacturing of specialty surgical instruments, pharmaceutical research regarding drug fabrication, dosage forms, delivery, and discovery, as well as manufacturing medical devices [62].

Some of the benefits of AM application in this segment are: customization and personalization of medical products, drugs, and equipment, but also cost-effectiveness, increased productivity, the democratization of design and manufacturing, and enhanced collaboration [62].

Application of 3DP in hearing aids has been increasing over time, and according to Phil Reeves, author of a report on the 3DP industry, in 2013 there were more than 10,000,000 3D printed hearing aids. According to Jenna Franklin, marketing associate with *EnvisionTEC* , a leading manufacturer of 3D printers for the hearing aid, claims that a majority of hearing aids in the world are using 3D printers [63].

Before implementing addictive manufacturing technology in the manufacturing of hearing aids, the conventional process was like artisanal production, and it took more than a week to produce it. Luckily today, 3D process involves scanning, modelling and printing can take less than a day.

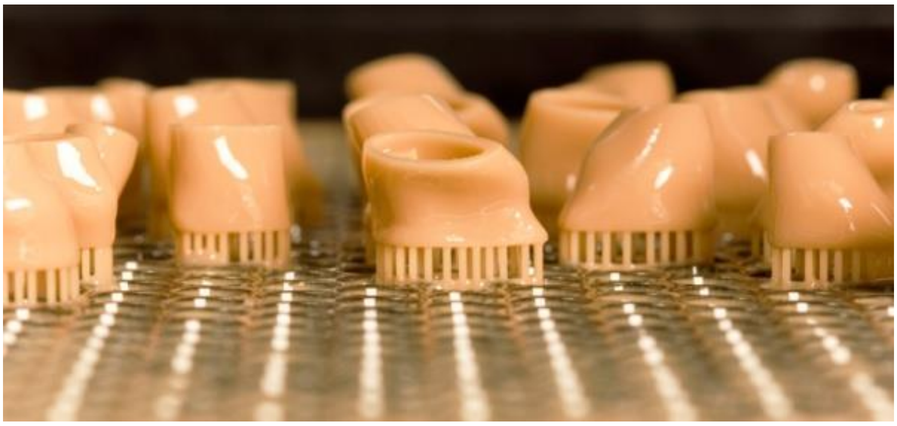

Figure 39 - Hearing aid produced by 3D printing [64].

3D printed protheses are also a good example of the influence this technique has, on one aspect is inexpensive, and on the other, it is totally customized to the wearer. Low costs of the 3D printed limb protheses are especially important in prosthetics for children, since they outgrow the prothesis fast.

As an example, *Open Biotics* is creating the next generation of prosthetic limbs, in a way that mechanical components are 3D printed, bringing along considerable cost-savings. Bionic hand can be very expensive, starting at about $35.000, reaching up to &120.000. This company is developing a bionic hand that offers the same functionality at under $1.200.

Figure 40 - 3D printing prosthetic hand [65].

3D printing not only shrinks the development costs of these bionic hands - it also allows for tailor-made designs to be implemented, that perfectly match the wearer's wants and needs [65].

From another angle, AM is also a great allied of combat support hospitals, in a way that they have restriction of weight and volume of equipment that they can transport to a field location. This restriction is a time-consuming process when it comes to bring more material from the military base.

To address this issue, US military conducted a 90-day evaluation of AM in producing on-demand, remote-site surgical equipment. This way, military demonstrated the feasibility of producing surgical equipment using commercially available AM devices. Electrical power, raw material, and digital design files for each instrument were all that was needed to print instruments on demand [61].

This new approach gives to military surgeons the ability to conduct more types of procedures, reducing the inventory, and decreasing uncertainty surrounding supply levels on the battlefield.

5.3.1. Challenges

The current challenges of AM's applications in the medtech industry may slow down the application of this technology in this sector, including the increased regulation, technology shortcomings, and a shortage of talent with AM printing capabilities.

The challenges discussed below are:

- Increased regulation;
- Structural strength;
- Speed and size;
- Talent shortage.

The regulation around AM products has been increasing over the last years, especially controversial application of AM in 3D-print guns. Because AM technology has the ability to manufacture other products that are normally subjected to regulatory control, the medical device sector falls into this category [62].

In the medical devices segment, the regulatory process to approve new device and new manufacturing process is length, as an example, in the US Food and Drug Administration (FDA) and other governing bodies, approval can take 7 to 10 years, before reaching market [61].

The structural strength of materials obtained by 3D printing is also a big limitation, that need more development and optimization. The normal process of AM occurs “layer by layer” which make end products with good resistance in X and Y planes, but are feared to lack equivalent strength on the Z plane [61].

Another challenge is the fact that can take hours to produce even small objects using AM, even if this is shortened by adjusting product thickness and size, this can lead to low quality finishing. Because of this limitation, AM process should be accelerated before local manufacturers adopt it into their industrial lines [61].

Finally, like in every sector in scope, a rise of this technology will require specific training, with this technology it’s no different. Skill will be required in the areas of computer-aided-design (CAD), building, operating, as well as maintenance training. Because AM is a relatively new technology, most of the training is offered in the job instead of informal training sessions, but if AM wants to continue its proliferation, there will be needed structured, comprehensive training and skills development [66].

6. Deciphering the future

3D printing is gaining, day after day, more space and importance in the services sector and in industries all over the world. Not too long ago, printing capacity were only suited for rapid prototyping, but in the coming years, 3DP will be the heart of full-scale production in several industries, from aerospace to automotive to health care to fashion [67].

AM has the potential to change today's complex supply chain, moving the manufacturer closer to the final consumer. The common effort of the huge supply chain advantages of 3DP, together with the consumer trends, will allow manufactures to save costs, serving consumers closer to where they live [68].

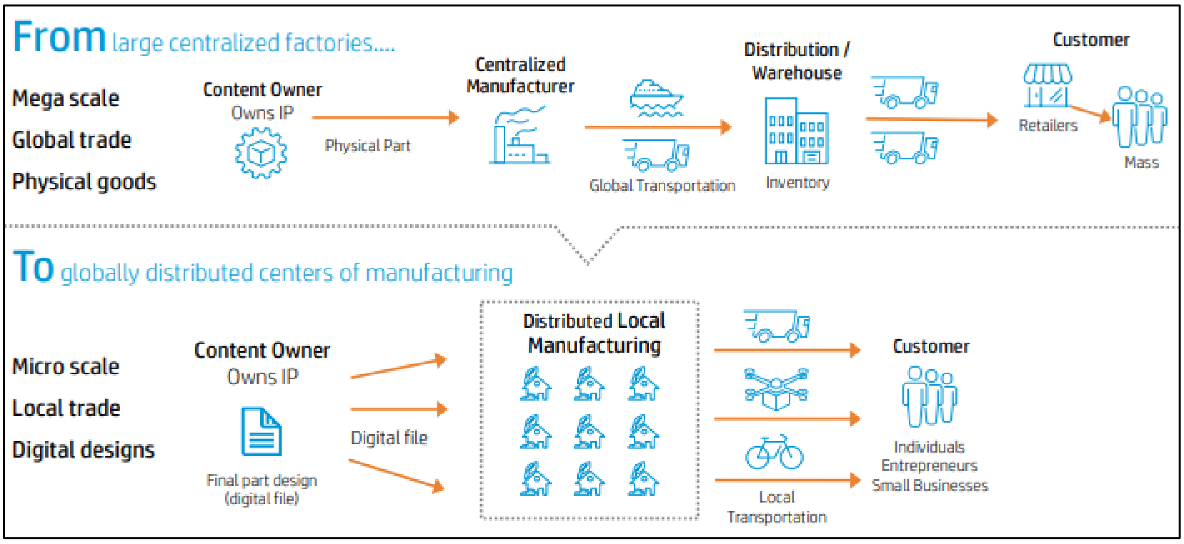

Figure 41 - Distributed Manufacturing Supply Chain [68].

One of the areas where predictions show big development is the innovation in direct-metal printing. The number of metal alloys that can be printed is on the rise, and they have exceptional performance characteristics. 3DP allow the creation of lightweight and complex pieces, that wouldn't be possible with traditional processes. With these changes, are expected more complex and high detailed products, critical for the aerospace, automotive and mechatronics industries, and soon this products will be available [67].

Companies like HP have entered in the market of 3DP, with technology that's speeds up production of selective laser-sintering parts. These important characteristics are the one that combined with the cost reduction of printing machines, will allow the mainstream of this technology [67].

Below are presented some forecast about the future impact that AM will have in the automotive, aerospace and MedTech industries.

6.1. Future paths of AM in Automotive

AM in Automotive industry will continue to thrive, spreading all across the industry, in these core applications [69]:

- **Design and concept communication:** high detail and accurate models are needed in automotive industry, to demonstrate designs and concepts of new models, as well as to test aerodynamic properties of the product designed;
- **Prototyping validation**: AM allows rapid prototyping in the pre-manufacture stage, which will secure AM place as one of the best technologies that allow quick printing to validate the model with a very good detail.
- **Preproduction and tooling**: According to many specialists, AM can be used to make moulds and thermoforming tools, which can and will allow to produce low cost tools and eliminate future losses in production when investing in high-cost tooling,
- **Customized part**: AM is already used, and has the potential to become one of the primer technologies to tailor the parts to specific vehicles, making them custom and lightweight.

Although automotive industry has been quick adapting AM into is process and to many applications, there's far more possibilities ahead, especially in the use of different materials [70].

Here are some areas where AM is expected to develop further in a near future [70]:

- Interior and seating;
- Tyres, wheels and suspension;
- Electronics;
- Selective laser Sintering (SLS);
- Framework and doors;
- Engine components;
- OEM components.

Customised functional products are currently becoming the trend in 3D printing as predicted by Wohler's Associates, who envisioned that about 50% of 3D printing will revolve around the manufacturing of commercial products in 2020 [9].

Another possibility of future developments of AM is the fact that this technology makes it possible to produce designs that have “conformal cooling” which directly integrate fluid-handling channels into the component, avoiding the need for separate cooling channels. In the future, automakers can benefit from the potential integration of mechanical and electrical functions through multi-material printing [46].

Advances in AM technology and adoption are leading to product innovations that will transition AM from a product design support tool to a conduit for the direct production of high-performance parts with fast turnaround.

Currently it takes years from initial design to final production before a vehicle hits the market. With AM, automakers can significantly shorten the development phase of the product life cycle and expand the growth and maturity phases [46].

A critical advantage in the near term of using AM is the potential production of components with lower weight, leading to vehicles with improved fuel efficiency, and this is a path where automakers are putting a great effort. In the long term, the simplification of parts with AM associated reductions in the complexity of assembly has the great potential to change design development and assembly processes [46].

It is expected that AM market in automotive sector reach 5.3 billion dollars in 2023, in terms of revenue and 12.4 billion dollars in 2028. This forecast of significant growth, between 2017 and 2028 shows that more and more players are adopting 3D technologies to design parts, functional prototypes or tools [71].

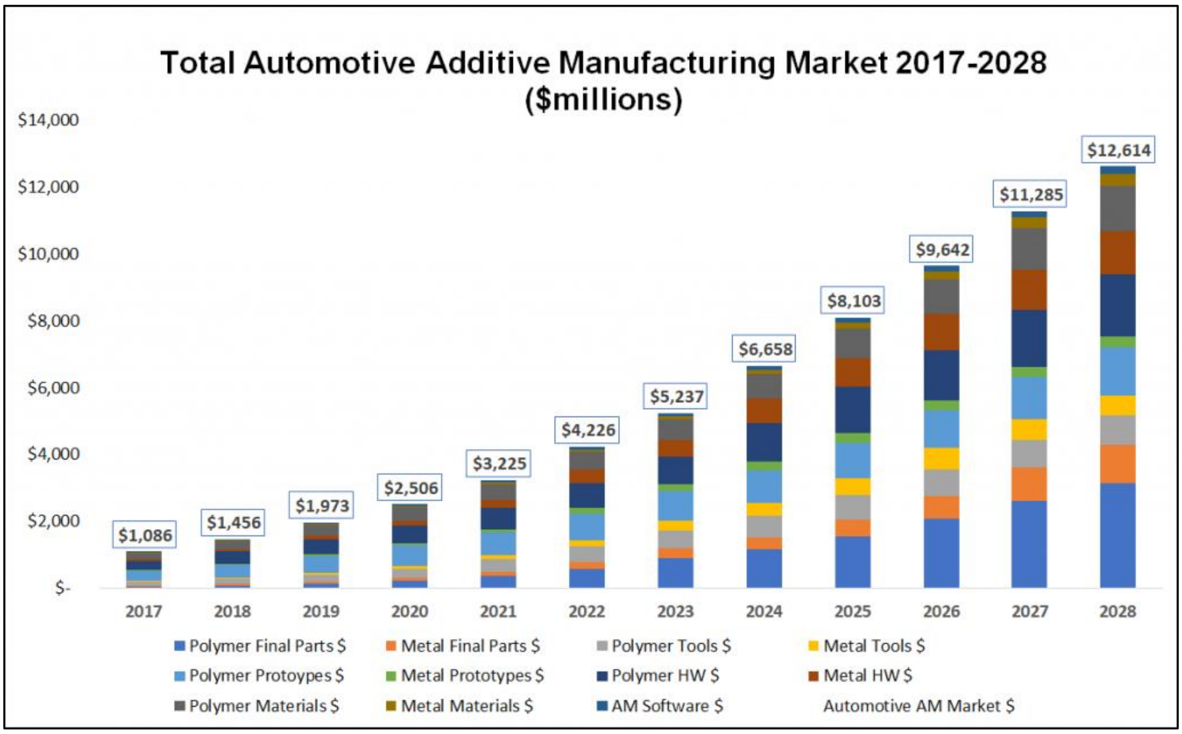

Figure 42 - Total Automotive AM market, forecast 2017-2028, in million ($) [71].

The growth of automotive additive manufacturing is an estimate that can be confirmed by several trends and developments. As an example, the arrival of *HP* in the AM market, thanks to the technology of Multi Jet Fusion can create complex parts faster. Other example is that market leaders as *Stratasys*, *3D Systems*, *EOS* and *Envision TEC* have developed more efficient AM solution by seeking to turn to mass production [71].

6.2. Future paths of AM in A&D industry

AM is quickly becoming a must-have for A&D manufacturers rather than just a luxury research and development project – with the A&D sector now contributing 12% of 3D printing's $3.1 billion global revenue. At same speed, A&D industry is expected to continue its growth trajectory in 2019, led by growing commercial aircraft production and strong defence spending [60].

A&D companies began experimenting with 3D printing as early as 1988, and industry leaders are now starting to recognize the unique capabilities of 3D printing and searching for ways to exploit them. The U.S. Navy is currently working on 3D manufacturing at sea, which would revolutionize the military support chain, while civil aviation companies such as Boeing and Airbus have been using the process to manufacture components for more than two years [54].

AM has the potential to revolutionize the industry in many ways [54]:

- Manufacturing parts with complex designs;
- Manufacturing components that require extensive machining;
- Reducing parts' weight;
- Reducing complex assembly efforts;
- Speeding time to market.

In the future, 3D printers will allow commercial aviation manufacturers to print parts for aircraft under construction, while defence manufacturers and service providers will produce replacement parts, on-demand, for damaged equipment to support defence operations [72].

A recent Oliver Wyman report warned that most aviation companies will have to completely overhaul their information technology (IT) systems to accommodate the changes 3D printing will bring [72].

The complex and specialty nature of A&D equipment makes for a vast support chain. The thousands of constituent parts required to assemble an aircraft or vehicle are typically sourced from companies scattered across the globe. With strict industry safety regulations, this poses a support chain problem for A&D firms, particularly when it comes to Maintenance, Repair & Overhaul (MRO). With utilization of spare parts, a key to keeping assets operational for the maximum amount of time, 3D printing offers a solution.

3D printing can build parts with designs and structures that help reduce the weight of a part without compromising its mechanical performance. For example, Rolls-Royce and General Electric have shown that they can produce lighter engines more quickly by incorporating 3D printing into their manufacturing process [73].

GE's 3D printed aircraft engine was presented in 2017, with its test flights occurring in 2018. In this engine, more than a third of is components will be built in through additive manufacturing methods. The engine will be part of the Textron Aviation upcoming 10-person business aircraft, the Cessna Denali [74].

Figure 43 – Jet engine and Cessna Denali aircraft (Textron Aviation).

The engine produced by Rolls-Royce, has successfully integrated 3D printed components and new materials into its Advance3 engine, to be available starting in 2025, is made up of around 20,000 parts, a significant number of which have been 3D printed [73].

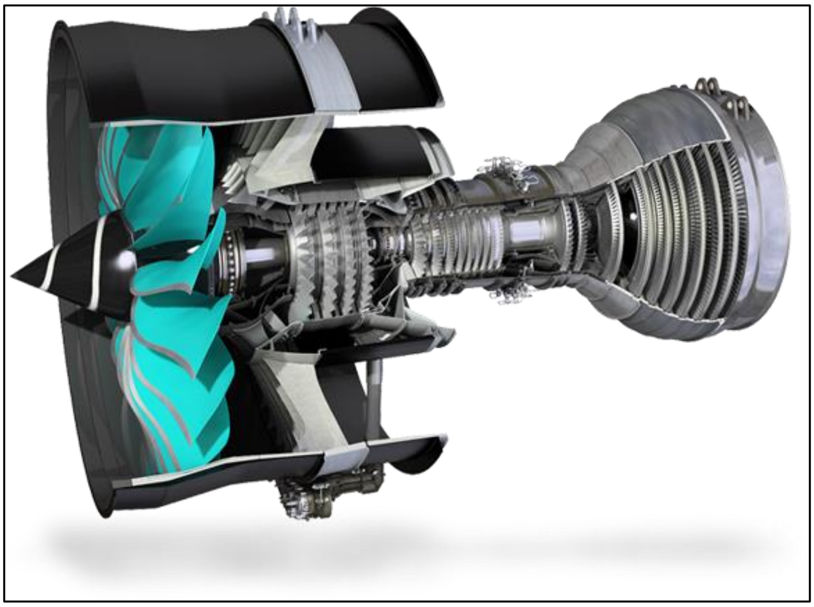

Figure 44 – Advance 3 engine Rolls-Royce ®.

Other area where are expected big developments is the spacecrafts industry. An article made by Robert Dehue also explained that Nasa is using a Stratasys 3D printer to develop and test a space rover. This rover will have a pressurized cabin to support life on Mars and currently contains over 70 printed parts [57].

Figure 45 – NASA's next rover feature [57]

6.3. Future paths of AM in Medtech industry

AM is predicted to have a significant growth in medtech industry, in particular the medical devices sector, as more companies come to appreciate its potential benefits across their supply chain and products.

Printing living issue using cells as ink is an exciting and very interesting area of prospective applications. The main future of 3D bioprinting is to reduce the shortage of supply in the organ donor market, despite that, current achievements are still too modest [62].

As an example, company *Organovo®*, using 3D bioprinter technology, created a human tissue, using model *ExVive3D.* The resulting tissue contain precise and reproducible architecture that can remain fully functional and stable for up to 28 days [75].

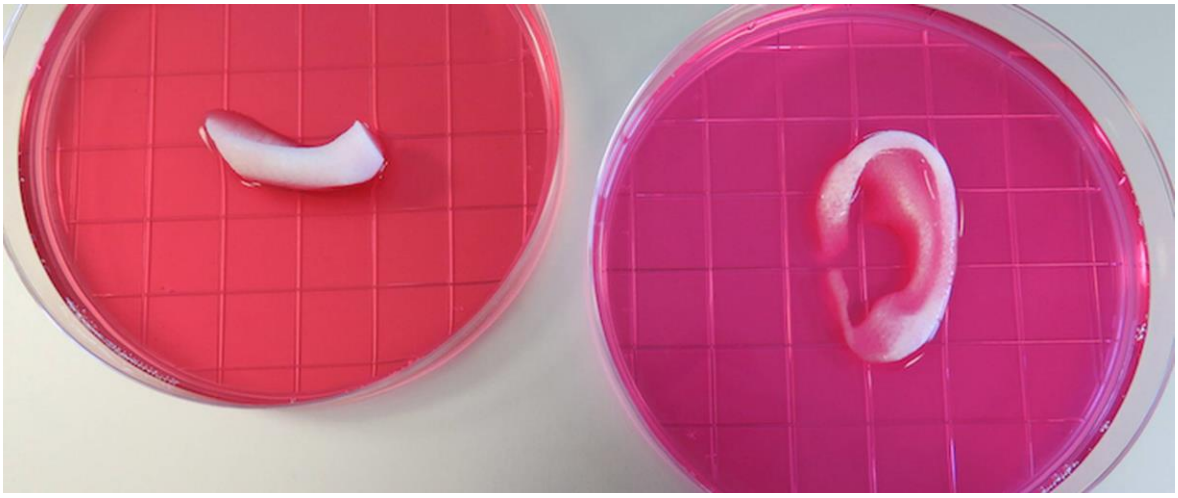

Figure 46 - 3D human tissue printed [76]

Researchers have been able to print sections of muscle, cartilage and bone, but they didn't successfully achieve its adoption into the human body [7].

A Chinese researcher at Hangzhou Dianzi University, Xu Mingen, developer of the "Regenovo" bioprinter, predicted that fully functional printed organs may be possible within the next 10 to 20 years [62].

Another future application of this technology is the drug segment. Lee Cronin's, at Glasgow's School for Chemistry, applied their 3D printed reaction ware to print the drug ibuprofen. There are several applications for drug printing, for example printing nonstandard doses for children or the elderly. On the other way, considering the possibility of drug abuse, many critics maintain scepticism over this domain.

The future of applications of 3DP in medicine is bright. Many indicators point to a extension and refinement of old and witnessing the birthday of new applications. Sometimes, the development will disrupt the whole field, like happened with the hearing aids market without bringing price reductions , but in general AM will revolutionize a huge part of MedTech sector [62].

7. Impact of AM

7.1. Conceptual Industry impact

The conceptual difference that AM technology brings to industries is the possibility of fabricating complex geometric shapes. This technology provides “complexity for free”, implying that it doesn’t particularly matter what the shape of the input object actually is, and that’s because a simple cube or cylinder would take almost as much time and effort to fabricate within the machine as a complex anatomic structure with the same enclosing volume [41].

The first step of product development is the concept and design phase, and this is an important step that defines the way the product will be developed and manufactured. Nowadays, companies have to their disposal two concept strategies, either they use a parametric concept (conventional process) or a direct modelling concept (recent process) [77].

In one hand, the conventional process is based on the design of products that can be manufactured by the traditional processes (casting, extrusion, cutting, drilling, etc.) and its usually called parametric concept[78].

On the other hand, he recent process allows the direct modelling, in a way that don’t impose constrains in the shape or format of the product. This recent conceptual process, also called topologic, has spread with the 3D printing development, and allow an enhancement of characteristics, that can be lighter, stronger and better looking [78].

During the 1980s and 1990s, much of the product development industry faced significant changes in structuring product development organizations. Many companies, like *Boeing*, and *Ford* reorganized product development teams of designers, engineers and manufacturing personnel, and other groups, building teams with hundreds of people, with the intention to allow transversal communication between all the product value chain. Currently, manufacturing engineers can understand decision rationale and start process planning and tolling development to prepare for the in-progress designs [41].

As an example of the recent concept brought to industries, we are going to analyse two different approaches for designing ducts for aircrafts.

Companies can use the typical approach using parts fabricated by conventional manufacturing processes (stamping, sheet metal forming, assembly using screws, etc). In contrast, the alternative approach (direct modelling) bring benefits like the reduction of assembly difficulties and cost by eliminating assembly operations. The result is a replacement of 16 parts and fasteners with 1 part that exhibits integrated flow vanes and other performance enhancing features [41].

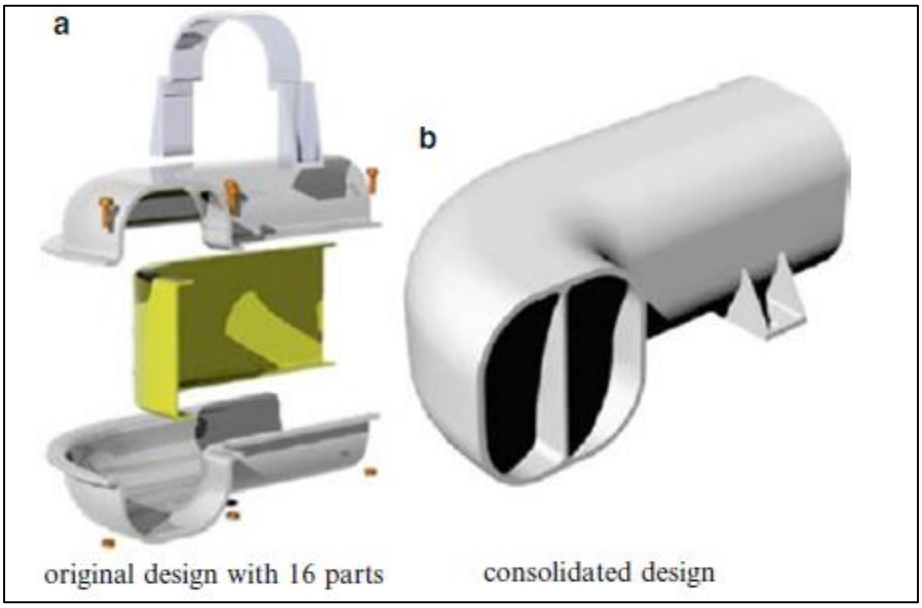

Figure 47 - Aircraft duct example [41].

In the opinion of industry analyst Monica Schnitger, president and founder of *The Schnitger Corporation*, “It might make sense to use direct modelling during conceptual thinking, when you need to quickly manipulate the design and don’t want to be slowed down by working within pre-defined rule. After that phase, she advice: “During detailed design, when most of the free thinking and exploring is finished, it might be reasonable to use parametric design to ensure that future iterations don’t violate the original concept.” [77].

7.2. Economic impact

The first set goal for 3DP was to accelerate the process of product development and their related production costs. As it was already mentioned, the waste related benefits of 3DP, yet again, and additive manufacturing process, surpasses, by far, subtractive manufacturing technologies like CNC, this, material and tool wise. Besides this, and, as well, the already mentioned structure, complexity, and problem solving of the newer prototype models, this process is considered really more beneficial in cases where the high financial and time expenditure necessary for the production of molds and tools for formative manufacturing exceeds the usually higher production costs per part in AM.

7.2.1. Market

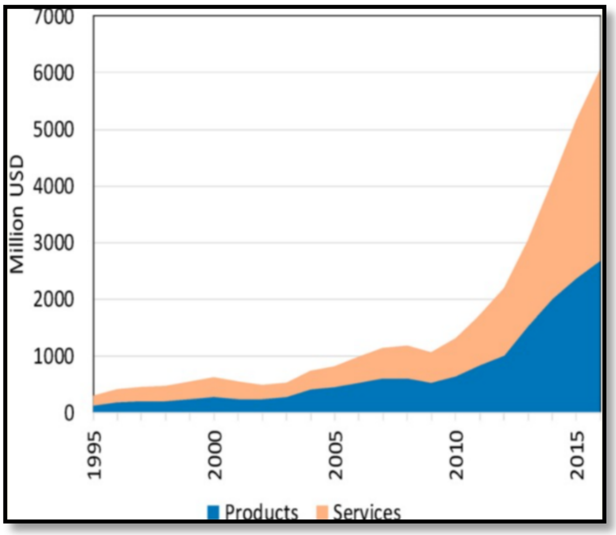

Figure 48 - Worldwide revenues from AM products and services between 1995 and 2016[14].

The significant overall market growth of AM is undeniable. Its revenues have grown since the 2008 crisis and worldwide numbers indicate it to surpass the 5 billion USD in 2015. This continuous growth is catching big market players' attention and the prospection of continuous growth.

Furthermore, the adoption of an AM system is still at an early stage. Sales of 3D-printed pieces have grown at a rate in excess of 25% per year since 1989, however, it is still not a much significant quantity when compared to the global manufacturing output. In 2017 the share AM took on the total manufacturing output was estimated, by a consulting firm and industry observer, to have been less than 1%[38].

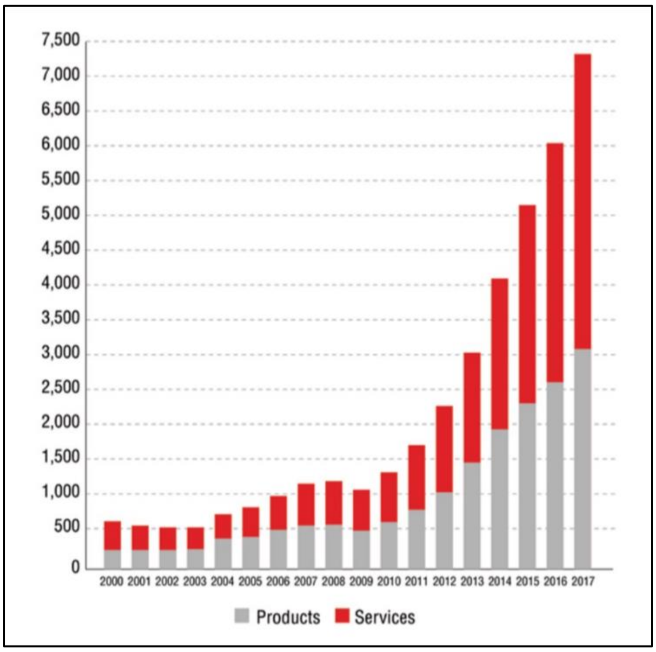

Figure 49 - Revenue for AM products and services worldwide [38].

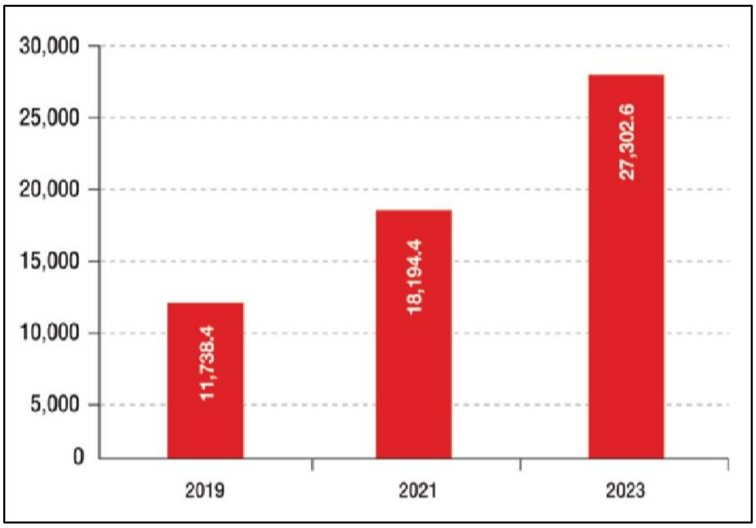

Figure 50 - Estimated future penetration of AM (US$M) [38].

Currently the wide range of materials being used in AM has proved to be advantageous market wise were the sales surpassed the value of 900 million USD in 2016 being the photopolymers the most commercialized one having been sold 350 million USD of them. The rest lies on a 127 million USD worth on metals and an estimated amount of 225 million USD spent on polymer powders for laser sintering. Therefore, it’s clear that polymers are the most used material[38].

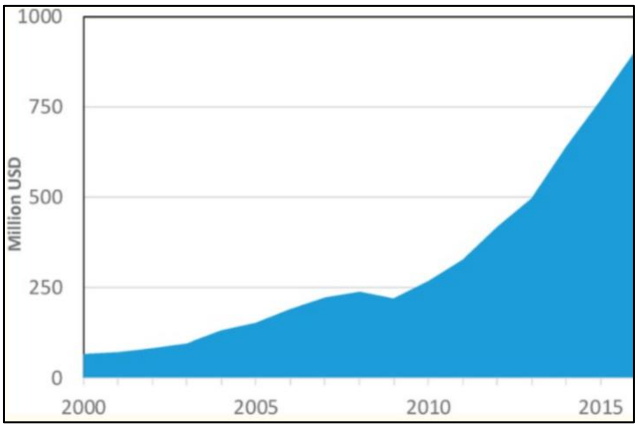

Figure 51 - Worldwide revenues from AM material sales between 200 and 2016 [14].

7.2.2. Process

Despite the economic benefits brought up by 3D printing, it is still unclear the part it will take on the industry as a mass production option for the creation of products. There will be a time where this process' liability will be better however, analysis from Wohlers Associates, a company that provides technical and strategic consulting on the new developments and trends in rapid product development and additive manufacturing, suggests that no more than 5% of future's manufacture will rely on additive manufacturing – "Not everything that can be 3D printed will be 3D printed" [79].

For basic geometry objects, AM is often slower and sometimes more expensive when compared to traditional processes so, it is unlikely for it ever to completely substitute them for the majority of more basic objects.

Cost wise, machines represent up to 70% of a 3D-printed object. And, even though the material waste in AM is way less than the one on traditional processes, the raw material cost in AM is much higher representing up to 30% of the total cost of a 3D-printed object which is a high value when compared to the 3% it represents on traditional processes.

Furthermore, AM items are rarely ready to go straight out of the printer, they might require some post-processing in the form of sanding, smoothing or assembly. These stages are done by hand which adds up to the overall cost of the product [38].

7.2.3. Distribution

The ability to manufacture products within one's facilities is a game changer when personalized parts are needed. Most of the times, besides the time it takes for those parts to be ready to be put to work in a factory's facility, the cost associated with the overall process of manufacturing and shipment is high.

In the Volkswagen factories, they are always looking for ways to make the assembly process easier, and so, from time to time they need parts capable of helping on the matter. So, they acquired a 3D printer to create these parts and, in 2016, they were able to save an estimated €150,000 just by doing so. For example, for a wheel protection jig used to hold the wheel in place, they had to wait 56 days and pay €800 for the part to arrive in the factory when, once they had the 3D printer, they were able to have the piece ready to go in a 10 day period and a cost of €21[38].

7.2.4. Warehousing for supply chains

An area that AM could have a great impact cutting costs is in warehousing. John Deere, an American producer of agricultural equipment, ships more than 450,000 orders a week. For that, he has a huge inventory, meaning, a lot of space to put the parts in. He has been working with Carbon, a supplier of AM equipment, to introduce "e-warehousing". Instead of storing the components in a physical space, he would upload his designs for parts and more in the cloud and, when needed, just print them in specified locations and then ship them. By 2060, time estimated by some to when AM reaches its full potential, and by doing so, we are also improving, by simplification, the supply chains where one could simply print on demand a part immediately at the location where it's needed. Stefanie Brickwede from Deutsche Bahn, a Germany railway company, says "We have €600m worth of parts in stock, just for rolling stock. If we can reduce this by printing on demand, this will be pure cash. This will affect contract logistics dramatically[38].

7.2.5. Companies relation with AM

The following data is relative to a study conducted by Sculpteo's 4th edition of "The State of 3D Printing). The study's methodology is based on interviews with 1,000 different respondents distributed globally. They are from a board range of industries including Aeronautic & Aerospace, Automotive, Consumer Goods, Education including students, Electronic and Electric, Healthcare, High Tech, Industrial Goods, Mechanic & Metal, and Services.

The following figure compares adoption rate of 3D printing applications and 3D printing users by department. It is worth mentioning the 21% increase on the production section between 2017 and 2018[38].

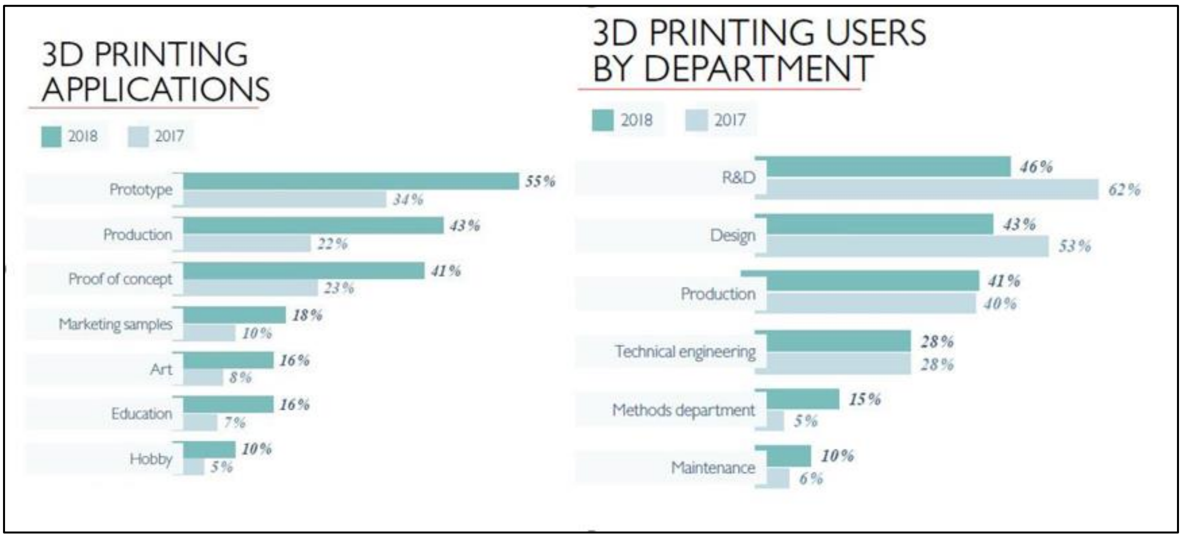

Figure 52 - 3D printing applications and users by department[31].

The benefits of 3D printing are clear by now and with the high requested customization 3D printing's top priority is accelerating product development.

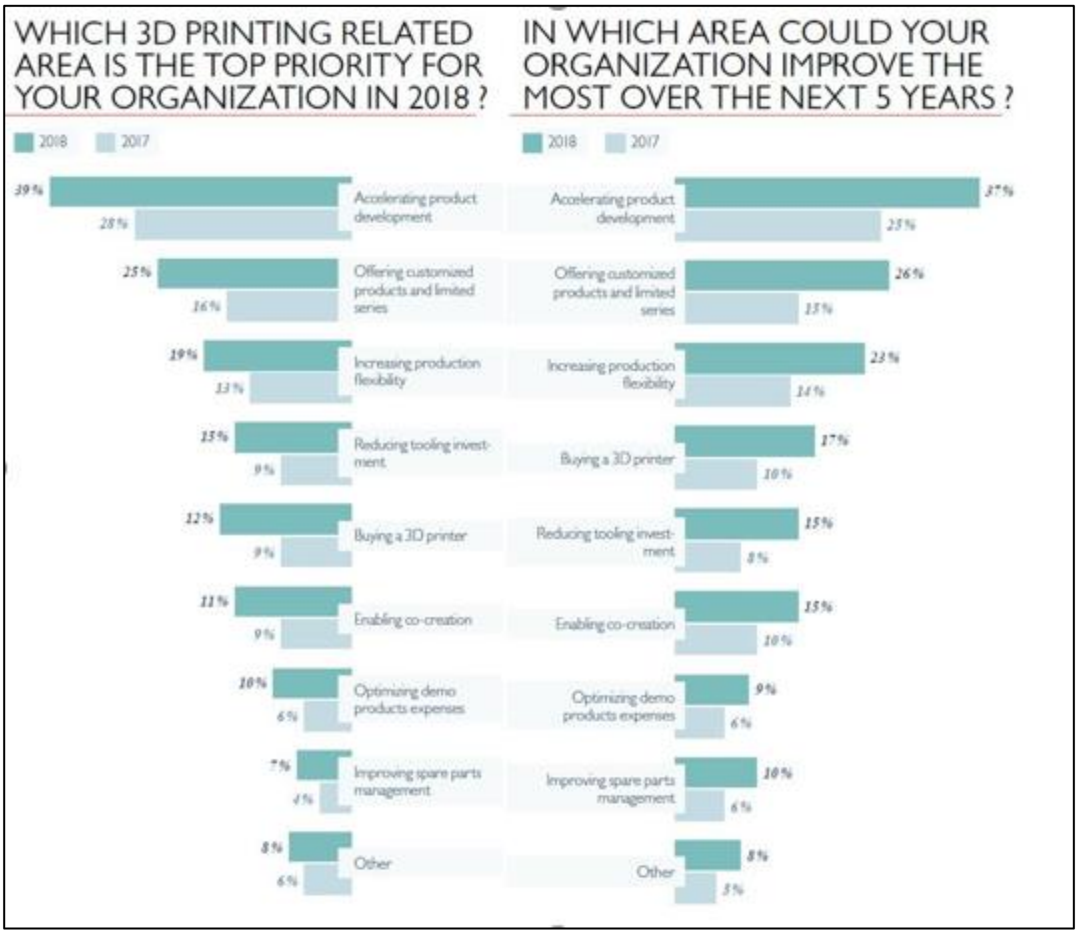

Figure 53 - 3D printing areas[31].

It is also worth mentioning the highest requested materials as well as technologies that are preferred by companies. This study has found that nearly all companies are relying on polishing and painting as part of their development process.

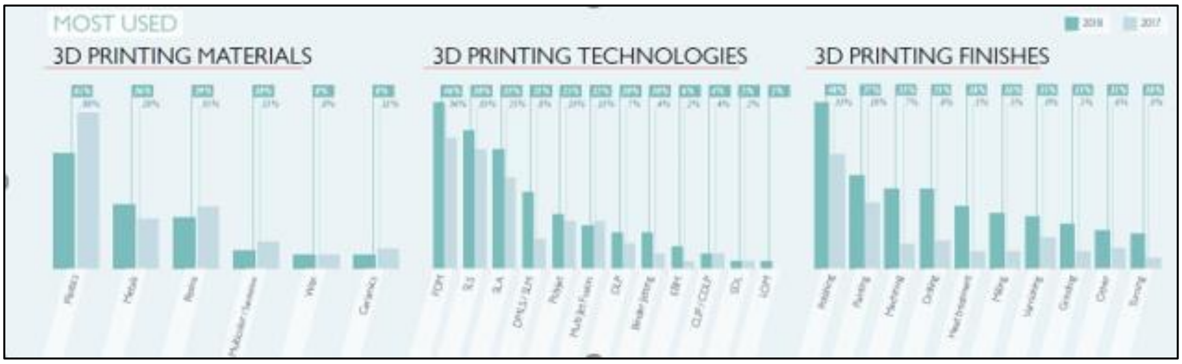

Figure 54 - 3D printing most used materials, technology and finishing[31]

The study as also found that 70% of the companies as increased their investments in

3D printing and that those that invest the greatest are the ones with the greater competitive advantage[31].

Interview 1 – Foundation CIM - UPC

This chapter is dedicated to the interview made to Felip Fenollosa i Artés, General Manager of the Foundation CIM-UPC, that took place on its headquarters, located in Spain, Barcelona on 22th January of 2019.

CIM-UPC it's a technologic center that provides practical support in the application of advanced techniques of production, combining services / projects / research and formation, either for academic, as for professional background.

Beginning of the interview, the first question was, which industrial sectors invest more in this technology (AM).

1) Felip told us that the biggest companies, Automotive, A&D and Medtech have invested heavily, but especially the small companies that want to develop innovative products have tried to know more of this technology, mainly due to the market globalization.

The second theme discussed was concerning the mass industrialization of 3D printing of metal pieces in common industry.

2) The main challenge is extending the metal fabrication in the industry because of equipment cost but is mainly sought after by companies with products with high added value. As an example, we have the A&D and the jewellery sector.

Next, a question of how and what were the main costs behind metal fabrication:

3) Felip told us that lack of human investment, especially incorrect operational techniques.

Another question was based on what the characteristic of greater need by the industries were.

4) Currently, a field of big investment is the possibility do print an object that is multi material.

Finally, we asked what the approach of Europe for this new type of technology should be.

5) He told that Europe is not for big series, but for small ones and with a big added value. That if the path that Europe and innovative technology centres should focus in order to thrive in this new paradigm of industrial production.

Interview 2 – Company AVINENT ®

This chapter is dedicated to the interview made to Albert Giralt Cadevall, General Manager of the *AVINENT Implant System*, that took place on its headquarters, located in Spain, Barcelona on 30th January of 2019.

This company works directly with the medtech sector and provides all the support of replacement and production of the prothesis, to integrate in the human body.

AVINENT is a company that, with its CEO says, faces a strong regulatory pressure and technical requirement on the products it provides. Since it works with hospitals around the world, and more directly with surgeons who need a particular prosthesis or 3D model to support the medical procedure.

A major concern that Albert Giralt tells us is the normative validation that additive manufacturing faced in his business. Since the production of the protests has to take place in a completely assured way, and the danger of contamination must be as small as possible. For this and other reasons, additive manufacturing in the same equipment is not a reality in the company, but what is done to overcome the problem of contamination is: manufacture the part in 3D equipment and then pass through the CNC.

Currently AVINENT has a vast and ever-growing catalogue of products, as new products/ prostheses are created. Currently, AVINENT manufactures 20 to 30% of dental implants by 3D manufacturing, while in traumatology, about 80% of the pieces are manufactured by 3D technology.

Albert points out that those who seek the services of the company, especially Hospitals and their medical professionals, have a lack of knowledge regarding the potential of additive manufacturing. Regarding suppliers, the criterion goes to the technological limitation since it is an area in constant development and the suppliers of machines have difficulty in integrating the latest technology in their equipment.

Conclusions

When an industrial revolution occurs, it changes drastically the way one or another thing is done. For the first revolution, water and steam where used to mechanize production, on the second, electricity to create mass production and the third, due to scientific and technology developments, electronics and information technology were used to automate production.

We are now facing a fourth industrial revolution that is characterized by the merging of the physical, digital and biological world to completely redesign industry management on the supply chain and essentially uproot industries. This happens with AM, however, isn't likely to topple existing mass production methods. Its use still only represents a small percentage of the overall worlds manufacturing industry. Cost related issues as well as process optimization and material search have delayed AM in mass production systems.

Nonetheless, companies that have adopted AM in their line of work have seen benefits and were able to have a return from it. By producing more elaborated components with more extreme designs and weight applications, as well as the reduction on the overall part lead time.

The totality of benefits brought by the adoption of AM in industries is still unclear but is easy to predict some of them. As it's becoming more adopted and improved, AM could lead to a broader redistribution of manufacturing, bringing business closer to the consumer whish changes up the logistics and distribution industry, reduction of inventory and warehouse facilities whish bring all the discussed economic advantages already presented.

For last, AM makes it possible for totally redesigned products and enables smaller companies, with not as much capital, to more easily enter competitors' market and flourish for them. Still unknown but AM can bring up some strong and long-term impacts. We will just have to stick around and see how it goes.

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Appendices

Table 1

Categorized AM Techniques for Polymers along with Advantages and Disadvantages

categorized techniques	typical and largest build volume	typical feature resolution	typical materials	advantages	disadvantages
Vat Photopolymerization					
exposure from top	250 × 250 × 250 mm^3 800 × 330 × 400 mm^3 (Prodways)	50–100 μm	acrylates/epoxides	excellent surface quality and precision	limited mechanical properties
CLIP	150 × 80 × 300 mm^3	75 μm	acrylates	high build speed	low-viscosity resins required
exposure from bottom	100 × 100 × 100 mm^3 300 × 300 × 300 mm^3 (DigitalWax 30X)	25–100 μm	acrylates/epoxides	low initial vat volume; better surface quality	limited mechanical properties
multiphoton lithography	5 × 5 × 1 mm^3 100 × 100 × 3 mm^3 (Nanoscribe)	0.1–5 μm	acrylates	very high resolution	low build speed; limited materials
Powder Bed Fusion					
polymer SLS	250 × 250 × 250 mm^3 1400 × 1400 × 500 mm^3 (Huake 3D HKS1400)	50–100 μm	PA12, PEEK	best mechanical properties; less anisotropy	rough surfaces; poor reusability of unsintered powder
Material and Binder Jetting					
polyjet	300 × 200 × 150 mm^3 1000 × 800 × 500 mm^3 (Objet 1000)	25 μm	acrylates	fast; allows multimaterial AM	low viscosity ink required
aerosol jet printing	200 × 300 × 200 mm^3 (Aerosol Jet 5X)	10 μm	conductive inks/dielectrics	high resolution; low temp process	low viscosity ink required
3D printing (binder jetting)	200 × 250 × 200 mm^3 1000 × 600 × 500 mm^3 (Voxeljet)	100 μm	starch, PLA, ceramics	fast; allows multimaterial AM; low temp	limited strength of parts; rough surfaces
Sheet Lamination					
laminated object manufacturing	170 × 220 × 145 mm^3 (Solidimension SD300)	200–300 μm	PVC, paper	compact desktop 3D printer	limited materials; low resolution; high anisotropy
Material Extrusion					
FDM	200 × 200 × 200 mm^3 1005 × 1005 × 1005 mm^3 (BigRep One)	100–150 μm	ABS, PLA, PC, HIPS	inexpensive machines and materials	rough surfaces; high temperature process
3D dispensing	150 × 150 × 140 mm^3 (3D Bioplotter)	100 μm to 1 cm	thermo-plastics, composites, photoresins, hydrogels, biomaterials	broad range of materials	rough surfaces; narrow viscosity process window